AN EVALUATION OF THE MARGINAL SHARPNESS OF THE PORCELAIN LABIAL MARGIN METAL CERAMIC RESTORATION

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John Joseph Boyle, Jr., B.A., D.M.D.

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John Joseph Boyle, Jr.

APPROVED:

Supervising Professor

May 17, 1991

Date

APPROVED:

Dean

DEDICATION

I wish to dedicate this thesis to the four people whose support has made this achievement possible.

The first person is my wife, Deborah. Her love, constant support, and patient understanding enabled me to devote the time and energy needed to complete this project.

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AN EVALUATION OF THE MARGINAL SHARPNESS OF THE PORCELAIN LABIAL MARGIN METAL CERAMIC RESTORATION

John Joseph Boyle, Jr., M.S.

The University of Texas Graduate School of Biomedical Sciences at San Antonio

Supervising Professor: Ronald B. Blackman, D.D.S., M.S.D.

The porcelain labial margin metal ceramic crown is an excellent restoration when anterior complete tooth coverage is indicated. This variation of the metal ceramic restoration eliminates the unsightly metal collar by allowing porcelain to form the labial margin at the gingival crest or supragingivally. Thus, the porcelain labial margin metal ceramic restoration combines the strength of a metal substructure with the esthetics of dental porcelain.

The porcelain labial margin fabricated by the platinum foil technique has an acceptable marginal opening and a sharp porcelain labial margin. In recent years, a direct-lift technique for porcelain margins has become popular because it is easier to fabricate and less expensive than the platinum foil technique. However, although the direct-lift technique produces an acceptable marginal

opening it also tends to produce a rounded porcelain labial margin. The rounding of the porcelain labial margin produces an unwanted gap at the porcelain-tooth interface, which may facilitate the retention of bacterial plaque and lead to irritation of adjacent gingival tissues.

In recent years, manufacturers have developed higher fusing shoulder porcelains specifically for the direct-lift technique. These shoulder porcelains reportedly are stable at high temperatures and will not round during firing. Such claims have not been scientifically substantiated in the literature to date. In fact, there is no reference in the literature to measuring the margin sharpness, or amount of rounding, of the porcelain labial margin. Yet the sharpness of a porcelain labial margin is critical to the clinical success of such a restoration.

The purposes of this study are to: (1) develop a technique using computer technology to accurately measure porcelain margin sharpness; (2) evaluate the accuracy of the high-fusing shoulder porcelains using the direct-lift technique to produce a sharp porcelain labial margin; (3) evaluate the accuracy of the high-fusing shoulder porcelains using the direct-lift technique to produce an acceptable marginal opening and uniform adaptation to the master die shoulder; and (4) evaluate the behavior of the high-fusing shoulder porcelains during fabrication of a porcelain labial margin metal ceramic restoration.

Uniformly prepared porcelain labial margin metal ceramic restorations were fabricated as follows: (1) platinum foil technique - using Vita VMK 68 body porcelain (Vident, Baldwin Park, CA) for the entire facial contour; (2) direct-lift technique - using Vita VMK 68 high-fusing shoulder porcelain (Vident) for the labial margin; and (3) direct-lift technique - using Vita's

SM 90 thermoplastic shoulder porcelain (Vident) for the labial margin. Vita VMK 68 body porcelain (Vident) was used to complete facial contours. Each group contained 10 specimens for a total of 30 samples. Marginal opening was evaluated from both a mid-facial and a cross-sectional view. In addition, a method was developed, using computer technology, to measure the external sharpness of the porcelain labial margin.

Statistical analysis of the data revealed the following:

1. The two direct-lift techniques produced significantly smaller facial marginal openings than the platinum foil technique.
2. The direct-lift technique using SM 90 shoulder porcelain produced a significantly greater internal marginal opening than either the platinum foil technique using conventional body porcelain or the direct-lift technique using high-fusing shoulder porcelain.
3. The direct-lift technique, using either high-fusing shoulder porcelain or SM 90 shoulder porcelain, produced a porcelain labial margin as sharp as that produced with the platinum foil technique.
4. The high-fusing shoulder porcelain and the SM 90 shoulder porcelain were accurate and stable enough to follow a rounding of the external shoulder margin of the stone die. This positive rounding or over-extended porcelain "tag" could present problems clinically when attempting to seat the restoration on the prepared tooth.
5. The limiting factor in the clinical success of the porcelain labial margin metal ceramic restoration may lie more with the ability of the die material to reproduce the clinical tooth preparation rather than with the dimensional change of the porcelain margin materials.

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

LIST OF PLATES

I. INTRODUCTION

The metal ceramic crown is one of the most popular restorations used in dentistry today, because it combines the esthetics of porcelain with the strength of a metal substructure. However, one of the limitations of this restoration is the presence of a cervical metal collar. If this metal collar is placed at the gingival crest or slightly supragingivally, it may create an unesthetic restoration. If this type of margin is placed subgingivally, the metal collar can adversely affect the health of the surrounding periodontal tissues. In an effort to circumvent these potential problems and yet maintain the superior strength of the metal substructure, the porcelain labial margin metal ceramic restoration was developed.

Various fabrication techniques for the porcelain labial margin have been described in the literature. The restoration when fabricated by a platinum foil technique has an acceptable marginal opening and a sharp external porcelain labial margin (Cooney et al., 1985). The direct-lift technique has become popular in recent years, because it is easier to master, less time consuming, and less expensive than the platinum foil technique. Although the direct-lift technique produces an acceptable marginal opening, it also tends to create a rounded porcelain labial margin (Hunt et al., 1978). This rounded porcelain labial margin produces an opening at the porcelain-tooth junction, which can permit the accumulation of food debris, bacteria, and plaque, and may promote periodontal disease (Waerhaug, 1975). The formation of this rounded porcelain labial margin is documented in the dental literature as occurring with the direct-lift technique (West et al., 1985). However, the nature and

degree of this rounding has not been well described to date.

Manufacturers attempted to solve this observed porcelain rounding problem with the development of "higher fusing shoulder porcelains." Their product literature states that these shoulder porcelains are stable at high temperatures and will not round during firing. These claims have not been independently substantiated in the dental literature.

The purpose of this study is to evaluate the accuracy of the direct-lift technique in fabricating the porcelain labial margin metal ceramic restoration as compared to the platinum foil technique. The direct-lift technique will use two different high-fusing shoulder porcelains and the platinum foil technique will use conventional body porcelain. Accuracy of fit will be determined by measuring both marginal opening and margin sharpness, the amount of rounding that occurs at the margin when porcelain is fired. As previously mentioned, measuring the amount of porcelain labial margin rounding has not been reported in the dental literature to date. Therefore, one aim of this study is to develop a technique using computer technology to accurately measure porcelain margin sharpness. Having a means to quantify the exact configuration of the porcelain margin will result in a more thorough and clinically relevant assessment of the porcelain labial margin metal ceramic restoration.

This study will also compare techniques and porcelain products in an effort to determine which materials or techniques provide the best marginal fit for the porcelain labial margin metal ceramic restoration.

II. LITERATURE REVIEW

A. Crown Margin Placement

Since its introduction in 1956, the metal ceramic crown has become one of the most popular restorations used in dentistry today (Brecker, 1956). With this restoration a metal coping is cast to fit a prepared tooth and a metal margin seals the crown. In areas of esthetic concern, a compatible low-fusing porcelain is fired to the metal substructure. As a result the metal ceramic restoration is an excellent restoration when full tooth coverage is indicated (Rosenstiel et al., 1988).

While treatment planning the metal ceramic restoration, the dentist must decide where to place the thin facial margin of metal. If it is placed at the gingival crest or supragingivally, the metal collar is visible. This "black line" margin is cosmetically unacceptable to many patients (Bertolotti, 1987). If it is placed subgingivally, then the metal margin can adversely affect the health of the surrounding periodontal tissues. Valderhaug and Birkeland (1976) assessed the tissue response to 389 complete crowns five years after cementation. Crowns with subgingival margins showed an increase in gingival inflammation and pocket depth in addition to loss of gingival attachment. On the other hand, the periodontal condition remained unchanged around supragingival margins. This same group of patients was reassessed as a ten-year follow-up, confirming the findings of the original study (Valderhaug, 1980). Becker and Kaldahl (1981) reported that plaque accumulation and gingival inflammation occur more frequently in teeth with subgingival crown margins than in those with supragingival margins.

These studies and other research call into question the belief that only

restorations with poor fitting margins promote the development of periodontal disease. It has been shown that even restorations with well-fitting but subgingival margins can play an important role in the etiology of periodontal disease (Mormann et al., 1974).

The technique of placing a margin subgingivally dates back to the teaching of Black (1891), as part of his thesis, "extension for prevention." Black advocated a "removal of the enamel margin by cutting from a point of greater liability to a point of lesser liability to recurrence of caries." He instructed dentists to "cut the enamel to such a point that the enamel margin will be self-cleansing, or be protected by the gum margin."

Bodecker and Applebaum (1934) were among the first to question Black's "extension for prevention" axiom. They felt that operative procedures used in placing fillings and crowns "loosened" the gingival attachment to the tooth, thus creating a wound by which infection may enter. They were uncertain if the natural resistance of the body could overcome this or whether long lasting harm would result, so they urged further research.

Orban (1941) reported that the epithelial attachment does not attach to the margin of a cast restoration. In fact, crown margins placed subgingivally apparently cause the epithelial attachment to migrate apically. Consequently, Orban advocated the placement of supragingival margins to promote a healthy periodontium.

Loe (1968) concluded that dental restorations extending into the subgingival area damage the periodontal tissues; either by promoting bacterial retention and/or by directly irritating the adjacent gingival tissues. Loe stated that the concept of "extension for prevention" was no longer valid and a new theoretical basis for the prophylactic treatment of caries and periodontal disease was needed.

There is ample research to show that restorations placed in contact with the gingival tissues adversely affected the health of the periodontium. For example, Waerhaug (1956) showed that rough surfaces facilitate the retention of bacterial plaque, which is the cause of gingival irritation. Zander (1958) found that the irregularities in subgingival margins accumulate plaque that the patient cannot completely remove. In a histologic study, Marcum (1967) showed that crowns with margins located below the gingival crest produced slight to severe gingival inflammation. And if these subgingival margins are open, significant bone resorption can result (Bjorn et al., 1969).

Larato (1969a) examined 546 cast gold crowns and found greater inflammation around those crowns that terminated beneath the gingival margin than those that were at or above the free gingival margin. Larato (1969b) then surveyed 613 patients with well contoured Class V composite resin, gold foil, or amalgam restorations. He reported that 26% of the gingival tissues adjacent to sound tooth surfaces showed signs of inflammation, while 73% of the tissues had gingivitis if adjacent to a subgingival restoration.

Silness (1970 a-c) examined the gingival tissues of patients with fixed partial dentures. Areas of the retainers with crown margins below the gingival crest had more severe gingivitis and periodontal pocketing was deeper than control areas.

Eissmann et al. (1971) reported that margins are not perfect. The junction between the restoration and the tooth surface always forms a crevice which may shelter bacteria and be a site for the retention of bacterial plaque. The key to successful margin placement is to minimize plaque retention, so it is recommended to place margins on tooth surfaces exposed to a cleansing action. A crown margin should form the smoothest possible transition from restoration to tooth surface.

Mannerberg (1971) constructed porcelain jacket crowns for central or lateral incisor teeth on 13 patients and placed the margins half the depth of the gingival sulcus. He recorded a greater volume of sulcular exudate from each crowned tooth than from its contralateral unrestored tooth. Mannerberg concluded that this increase in sulcular fluid, being a measure of the inflammatory reaction present, would remain constant even if the patient's oral hygiene was good, although no evidence was provided for this particular conclusion.

Richter and Ueno (1973) attempted to overcome the variables of looking at contralateral teeth by placing crown margins both above and below the free gingiva on the same tooth surface. They used the buccal surface of the mandibular first permanent molar in each case and constructed 12 crowns, one each for 12 patients, which they checked annually for three years. The gingival index of three crowns indicated an increase in inflammation in areas where the crown margin had been placed subgingivally.

Newcomb (1974) later studied the degree of gingival inflammation associated with subgingival crown margins located at different levels within the gingival sulcus. He found a very strong negative correlation between gingival inflammation and the distance of the crown margin from the base of the sulcus. The closer a subgingival crown margin approaches the base of the gingival sulcus, the more likely it is that severe gingival inflammation will occur. In this study the least inflammation was noted with crown margins placed at the gingival crest.

Waerhaug (1975) examined 108 extracted teeth and found 90% of the restorations covered with plaque subgingivally. Some subgingival restorations were covered with plaque in as short a time as six weeks. He reported that sooner or later plaque will accumulate on most, if not all, subgingival

portions of a restoration. Furthermore, rough surfaces and inadequate marginal adaptation both facilitate more rapid adherence of bacteria to restorations than to smooth tooth surfaces. Wilson and Maynard (1981) agreed with Waerhaug's findings and demonstrated that a metal ceramic restoration has irregularities between the metal collar and the porcelain as well as at the margin itself. They questioned the ability of patients to adequately clean restoration margins that extend into the gingival sulcus.

An in vivo study by Lang et al. (1983) revealed that overhanging subgingival margins changed the subgingival microflora to resemble chronic periodontitis. There was an increase in gram negative anaerobic bacteria and Black-Pigmented Bacteroides.

Ericsson and Lindhe (1984) reported that placement of a restoration subgingivally allowed plaque to accumulate and established conditions which promoted the development of moderate to severe gingival inflammation. Furthermore, in experimental sites characterized by an inadequate width of keratinized gingiva, the inflammatory reaction was almost always accompanied by an apical displacement of the soft tissue margin.

Hunter and Hunter (1990 a-b) acknowledged that periodontal tissue destruction is a complex process, and they advocated sufficient axial tooth reduction to allow fabrication of appropriately contoured crowns.

There have been numerous studies describing the adverse effects of subgingival crown margin placement. But it was Maynard and Wilson (1979) who explained it best with their concept of the "biologic width." The biologic width is the physiologic dimension of the periodontium in contact with tooth structure that cannot be violated. Maynard and Wilson studied what Wheeler (1961) had previously described as the biologic preservation approach to margin placement. Wheeler contended that the traditional approach of always

placing crown margins "beneath the gum" was outdated. He stressed a biologic approach whereby "margins may be placed at any level that will perfect the form and preserve the periodontal attachment." Maynard and Wilson (1979) indicated that subgingival margins encroaching on the periodontium's biologic width caused marginal and papillary gingivitis which could then progress to chronic inflammation, bleeding, pocket formation, periodontitis, and marginal tissue recession. Consequently, they advocated supragingival crown margin placement.

Block (1987) also cautioned against encroaching upon the gingival attachment complex. He observed that frequently a healthy sulcus will probe less than one millimeter. In such cases, a restoration should not enter the sulcus but terminate just at or above the free gingival margin.

In defense of the restorative dentist, Preston (1977) listed six factors that dictate subgingival margin placement: 1) caries below the free gingival margin; 2) the need to get beyond a previous restoration onto sound tooth structure; 3) cemental sensitivity on the tooth being prepared; 4) the need for retention on a short clinical crown; 5) restoring a fractured tooth; and 6) cosmetic demands of the patient. The cosmetic demands of the patient are most often the reason cited for extending a crown margin into the gingival sulcus. Obviously, subgingival margins are more esthetic and are pleasing to both patient and viewer. However, we should also consider the potential esthetic result of gingival inflammation, with its accompanying redness, bleeding, shiny appearance, and edema resulting from subgingival margins (Palamo and Peden, 1976).

Recently Bader et al. (1991) examined the margins of cast restorations in 831 patients who had received regular professional dental care for the past five years. He found significantly greater gingival inflammation and deeper

probing depths associated with subgingival cast restoration margins. Bader concluded that even among patients receiving regular preventive dental care, subgingival margins are associated with unfavorable periodontal responses.

B. Evolution of Porcelain Labial Margins

In an attempt to satisfy the esthetic demands of the patient and maintain the health of the periodontium, clinician's modified the margin of the metal ceramic crown.

Some thinned the facial collar of metal significantly in an attempt to visually eliminate it. But Donovan and Prince (1985) found that these margins could distort when the porcelain was fired, greatly compromising the fit of the restoration. One advantage of a beveled shoulder margin is that it affords protection against distortion during porcelain firing (Hobo and Shillingburg, 1973).

Others covered the facial collar of metal with porcelain in an attempt to hide it from view. This modification cannot be done without overcontouring the restoration which can lead to gingival irritation (Preston, 1977). Reshaping an overcontoured crown will expose the opaque layer, and produce a "white line" around the cervical aspect of the crown. Unfortunately, exposed opaque cannot be suitably polished or glazed. This roughened surface can present itself as a nidus for plaque accumulation and subsequent gingival pathosis (Sozio, 1977).

Stein and Kuwata (1977) found that porcelain extended onto the facial collar is not adequately supported at the margin. This overextended porcelain is susceptible to fracture when the metal flexes, leaving rough metal or opaque porcelain exposed to irritate surrounding gingival tissues.

One method of eliminating a metal collar is to use the very esthetic

porcelain jacket crown restoration. But problems with this restoration include brittleness and a lack of tensile strength. The weakness is caused by the propagation of surface microcracks which, when placed under tensile loads, lead to fracture (McLean, 1980; Shillingburg et al., 1987).

Much research has been directed toward improving the strength of the porcelain jacket crown. McLean and Hughes (1965) incorporated aluminum oxide crystals into the porcelain to increase its resistance to fracture. Sherrill and O'Brien (1974) found the aluminous porcelain superior to feldspathic porcelain in transverse strength. However, Southan and Jorgensen (1972b) reported that aluminous porcelain crowns still fractured due to the propagation of microcracks located on the internal surface of the porcelain jacket crown restorations.

Other researchers attempted to strengthen the porcelain jacket crown and eliminate the internal surface flaws by bonding aluminous porcelain to an oxidized layer of tin applied to platinum foil (McLean and Sced, 1976; Sced et al., 1977).

McLean et al. (1978) introduced the twin foil technique, using two layers of platinum foil to fabricate a porcelain jacket crown. The inner foil was used to achieve a porcelain butt fit at the shoulder and was not plated. The second foil was adapted over this inner foil, cut short at the axio-gingival line angle, and tin plated to achieve a chemical bond with the aluminous core porcelain. After crown fabrication, the inner, unplated foil was removed, leaving a porcelain butt margin with foil bonded to the aluminous core porcelain.

Upon investigation, Munoz et al. (1982) and Philip and Brukl (1984) found the platinum-twin foil jacket crowns significantly weaker in compressive strength than conventional aluminous porcelain jackets.

Oram et al. (1984) compared the tensile strengths of the various porcelain jacket crown fabrication techniques: standard aluminous porcelain, tin plated platinum foil, and the twin foil system. They found that incorporating foil increased the tensile strength by approximately 50%. They also found that the tensile strength of a metal ceramic crown was 50% greater than the strongest porcelain technique.

Given these findings, an alternative would be to fabricate the metal ceramic restoration without the labial margin restored in metal -- have a butt-joint of porcelain as the gingival margin. Such an approach would combine the strength of the metal ceramic crown with the esthetics of the porcelain jacket crown at the margin (Dykema et al., 1986). Currently, this restoration is known as the porcelain labial margin metal ceramic restoration.

In discussing gingival esthetics, Goodacre (1990) stated that the best way to enhance gingival health and minimize tissue trauma is to avoid contact of the gingiva with restorative materials. For those patients who display the cervical aspect of their teeth, it is possible to avoid gingival contact and meet esthetic requirements by using porcelain labial margin metal ceramic restorations with finish lines located at the gingival crest. In situations where gingival recession or periodontal disease has resulted in exposed root surfaces, it can be esthetically and biologically advantageous to use porcelain labial margin metal ceramic restorations with supragingival finish lines.

C. Dental Porcelain

Dental porcelains are ceramic materials classified in three groups according to their maturation or fusion temperatures: high-fusing (1290^{o} to 1370^{o}C [2350^{o} to 2500^{o}F]), medium-fusing (1090^{o} to 1260^{o}C [2000^{o} to 2300^{o}F]),

and low-fusing (870^{o} to 1070^{o}C [1600^{o} to 1950^{o}F]) (Phillips, 1982). It is the low-fusing porcelains that are used in the fabrication of metal ceramic restorations.

The principal constituents of dental porcelain are feldspar, quartz, and alumina. Feldspar is the main component and is responsible for glass formation. There are two types of feldspar: potash feldspar and sodium feldspar. Potash feldspar increases the viscosity of the molten glass to control translucency and pyroplastic flow, while the sodium feldspar lowers the fusion temperature with no increase in translucency (Naylor, 1986). Quartz is difficult to melt by firing so it serves as the glass forming matrix of dental porcelain. It increases the strength of porcelain, but also reduces translucency. Alumina increases the viscosity and hardness of the glass network. As a result, dental porcelain has a high resistance to pyroplastic flow, which is necessary to obtain the desired configuration of the restoration.

To manufacture dental porcelain, the raw ingredients are mixed together and heated to a high temperature, where chemical reactions cause the mixture to fuse. The fused mass is then quenched in water. As a result, the glass is stressed to the extent that considerable cracking and fracturing occur. The process is known as fritting, and the product is called a frit (Phillips, 1982). Such a brittle structure can be readily ground to a fine powder. During subsequent firing, little or no pyrochemical reaction occurs. The particles are merely fused together.

Dental porcelain is received from the manufacturer in powder form, which is mixed with a water-based glycerin-containing liquid to form a paste of workable consistency. This mixed mass then is used to make a restoration with the needed shape. Several condensation techniques (i.e. vibration and

blotting) are used to remove as much excess liquid as possible. The porcelain particles are drawn together during condensation by capillary action. When the mass is fired in a porcelain oven, individual porcelain particles fuse to form a continuous mass by this sintering process. As the particles fuse, the surface tension and viscosity of the fused mass draws portions toward the area of greatest bulk. Consequently, a loss of interstitial space occurs accompanied by as much as a 37% volumetric shrinkage after firing (Craig, 1989).

An additional consequence of firing porcelain is that microcracks, which may measure less than 0.2 micrometers wide, form on the surface of the porcelain (McLean, 1980). These microcracks are formed as the external surface of the porcelain cools more rapidly than the internal surface forming an external "skin" surrounding the still molten center. The "skin" may partially prevent the center from undergoing complete thermal contraction upon cooling. This uneven cooling creates tensional stresses within the porcelain that can distort or rupture the outer skin, producing microcracks (Phillips, 1982). Griffith (1920) and Duckworth (1951) theorized that the microcracks act as stress concentrators. When their critical stress is exceeded, the microcracks propagate through the porcelain and can actually cause the procelain to fracture. Consequently, the true strength of the porcelain is determined by the most highly stressed flaw or crack (Shelvin and Lindenthal, 1959).

Compressive forces tend to inhibit the propagation of the microcracks, whereas tensional forces appear to promote their propagation (McLean, 1980). Therefore, porcelain is more resistant to compressive forces than to tensional forces. Dental porcelain has a compressive strength of approximately 25,000 psi, but tensile strength of only 5,000 p.s.i. (Craig, 1989). It is the tensile forces that are responsible for the fracturing of dental porcelain

(Southan and Jorgensen, 1973).

Porcelain stress is of particular concern when examining porcelain labial margins. McLean and Sced (1976) stated that the bending and torsional stresses placed in the incisal third of a restoration from occlusion, can initiate tensile stresses within the crowns, particularly in the cervical area. Derand (1973) also felt the facial margin was an area of high tensile stress concentration. Prince et al. (1983) stressed the importance of not angling a shoulder greater than 90^{o} to the tooth's long axis in the collarless crown preparation to reduce the forces of tension which lead to fracture. However, Anusavice and Hollatie (1987) analyzed stress distribution in the porcelain-margin, metal ceramic crown and found that the maximum tensile stress in porcelain is 1100 psi, and it occurs in the facial region approximately 3.2 mm from the incisal edge. This is well below the tensile strength value (5000 psi) generally reported for feldspathic porcelain. The principle stresses within the gingival region are compressive in nature and they too are well below the compressive strength of porcelain (25,000 psi).

Brackett et al. (1989) evaluated the effect of various surface treatments on the tensile strength of porcelains used in fabricating porcelain margins. They found that the tensile strength of porcelain treated with an applied glaze was significantly greater than porcelain treated with either a natural glaze or natural glaze and polish. They theorized that the applied glaze may have the ability to flow into the surface flaws of the porcelain and prevent them from becoming the initial point of fracture when the porcelain is stressed. The overglaze may also act as a sealant, preventing any internal crack propagation from reaching the external surface.

Southan (1988) stated that chemical strengthening is the only method of strenghtening glasses without a noticeable decrease in optical density. His

research, using conventional aluminous porcelain for jacket crowns, showed that ion exchange can result in strength increases of greater than 95%.

Campbell (1989) also believed that the ultimate failure of dental porcelain is due to tensile stresses. The different flexural strengths of the substructures on to which porcelain is veneered impart different tensile stresses to the ceramic veneer. Campbell examined the porcelain substructures and found that metal ceramic specimens were 45 to 70% stronger than veneered ceramic substructures.

D. Plaque Retention of Porcelain

Placing the labial margin in porcelain is an obvious esthetic improvement for the metal ceramic crown. However, what effect does the porcelain material itself have on the neighboring gingival tissues?

Glantz (1969) discovered that plaque formed in greater volume and adhered for a longer period of time to restorative materials than to dentin and enamel. Waerhaug (1956) showed that plaque retention increases with increasing surface roughness of the restorative material and urged thorough polishing of any restoration near the gingival margin. Clayton and Green (1970) examined various dental materials and agreed -- restorative surfaces in contact with tissue must be smooth.

Volchansky (1974) used a scanning electron microscope to evaluate the surface characteristics of natural and restored surfaces adjacent to gingival tissues. He found that porcelain was smoother than either gold or amalgam.

Kaqueler and Weiss (1970) found that glazed porcelain was the restorative material that accumulated the least amount of plaque. Furthermore, Newcomb (1974) reported that plaque indices for porcelain were lower than those for adjacent natural teeth.

Wise and Dykema (1975) also believed the adherence of plaque could be affected by the material. Their study revealed that porcelain had statistically significant lower plaque retaining capacity than metal ceramic alloys or Type III gold. The greatest differences occurred where patient cleaning was minimal.

In vitro studies by Dummer and Harrison (1982) and Tullberg (1986) found very low adhesive forces between dental plaque and ceramic surfaces. An in vivo study by Chan and Weber (1986) found that dental ceramics exhibit low plaque retention and these surfaces are easily kept clean by the patient.

Sorenson (1989) evaluated plaque accumulation on metal ceramic restorations and ranked the materials in order of decreasing accumulation: 1) aluminum oxide abraded metal (most plaque), 2) opaque porcelain, 3) polished metal, 4) glazed porcelain (least plaque).

Adamczyk and Spiechowicz (1990) investigated plaque accumulation on the various materials used for fixed prostheses: human enamel, metal, acrylic resin, and glazed porcelain. This microscopic evaluation of glazed porcelain showed very loose packing of small quantities of plaque. During this same period of time and under the same conditions, much larger amounts of plaque accumulated on metal and acrylic resin restorations. The scanning electron microscope investigation verified the earlier conclusion of Volchansky (1974) - the surface of glazed porcelain was the smoothest of the materials studied.

Therefore, from a materials standpoint, glazed porcelain is the material of choice for restorations that will be in contact with gingival tissues (Rosenstiel et al., 1988).

E. Marginal Fit of Porcelain Labial Margins

The quality of marginal fit not only plays an important role in the

prevention of secondary caries but also influences the reaction of the surrounding periodontium. Bjorn et al. (1970) demonstrated a positive correlation between defective crown margins and a reduction in the height of the interdental alveolar bone. They reported that most margins of full coverage restorations did not fit and in many cases the cement film thickness at the defective margin was greater than 200 micrometers. This degree of marginal opening provided an ideal site for plaque accumulation and the growth of microorganisms.

A review of the literature revealed a wide range of what clinicians consider an acceptable crown fit. Christensen (1966) showed that gingival margins with openings up to 119 micrometers were accepted by experienced restorative dentists when they could not visualize the margin. Visualized margins were accepted with openings up to only 39 micrometers. McLean and von Fraunhofer (1971) evaluated 1000 porcelain crowns over five years and found that restorations with marginal openings up to 120 micrometers could be considered clinically acceptable. Dedman (1982) reported that dentists accepted openings up to 93 micrometers for overhangs and up to 114 micrometers for margins they could not see directly. In a recent study of the marginal fit of various ceramic margins, Hung et al. (1990) concluded that the practical range for clinical acceptability of fit appeared to be in the 50 to 75 micrometer range.

Research on the fit of porcelain labial margins has shown the porcelain fit to be equal to or better than alternative margin designs when evaluated by marginal opening. Schneider et al. (1976) obtained a mean marginal opening of 38.8 micrometers for porcelain shoulders of porcelain labial margin metal ceramic crowns fabricated with a refractory die material. Hunt et al. (1978) produced restorations with marginal openings in the 12.0 to 17.0 micrometer

range before cementation and 14.7 to 34.8 micrometers after cementation with zinc phosphate cement.

Vryonis (1979) compared porcelain shoulder margins to gold margins made on the same die. The porcelain margins were much better, with a marginal gap of 5 to 10 micrometers, whereas the gold margins measured in the 17 to 34 micrometer opening range.

Belser et al. (1985) examined the fit of three types of metal ceramic crown margins in vivo. They found no significant difference among beveled metal margins, metal butt margins, or porcelain butt margins before or after cementation. This study demonstrated that it was possible to produce porcelain labial margins with marginal openings less than 50 micrometers. Studies by West et al. (1985) and Belles (1987) also confirmed that porcelain labial margin openings less than 50 micrometers were consistently achieveable.

Cooney et al. (1985) compared mean marginal openings to evaluate the various porcelain labial margin fabrication techniques. They reported that the platinum foil technique gave a significantly better fit (32 to 38 micrometers) than a wax binder technique (81 micrometers) or a direct-lift technique (70 micrometers).

Donovan and Prince (1985) analyzed margin configurations for metal ceramic crowns. Based on a review of the literature, they concluded that marginal gaps of only 5 to 34 micrometers can be consistently obtained using all-porcelain labial margins.

Wanserski et al. (1986) measured the marginal adaptation of shoulder porcelain (Vident, Baldwin Park, CA) using a direct-lift technique. They found a mean marginal opening of 15 micrometers for a shoulder porcelain margin versus 20 micrometers for a metal margin. They concluded that the direct-lift technique is a consistent method of achieving clinically

acceptable all-porcelain margins. Omar (1987) also evaluated shoulder porcelain (Vident) with the direct-lift technique and concluded that his 33 micrometer marginal opening was also within clinically accepted limits. Arnold and Aquilino (1988) obtained similar results (38 micrometer marginal opening) with their evaluation of the direct-lift technique using shoulder porcelain (Vident).

Recently Abbate et al. (1989) compared the marginal fit of various ceramic crown systems. Their results showed no significant statistical difference in marginal fit between metal margins or shoulder porcelain margins fabricated from the same tooth preparation.

F. Porcelain Labial Margin Fabrication Techniques

A porcelain labial margin can be fabricated using any one of three different techniques: platinum foil, refractory die, and direct-lift.

1. Platinum Foil Technique

The platinum foil technique is a metal ceramic adaptation of the twin-foil technique (McLean et al., 1978) for fabricating porcelain jacket crowns. In this technique porcelain is condensed and fired against a platinum foil matrix that is not removed until final finishing.

Johnston et al. (1967) swaged a 0.001 inch piece of platinum foil over the gingival and proximal shoulder of the die. The crown substructure was then formed in wax over the foil. This assembly was subsequently cast in a gold-based metal ceramic alloy so the foil could be incorporated into the casting. This procedure was extremely technique sensitive as the foil was easily damaged while divesting the casting. To remedy this problem, Goodacre et al. (1977) spotwelded the platinum foil to the crown coping after it had

been cast and finished. They condensed conventional body porcelain against the foil to form the entire shoulder and labial margin.

Choung et al. (1982) used gold powder and oven soldering to fuse the platinum foil to the casting instead of spotwelding it. They felt they could remove excess foil from inside the casting enabling it to fit the die more accurately with its attached foil matrix.

Lacy (1982) placed what he called a "combustible resin" on the platinum foil before adding the first body bake of porcelain in an attempt to reduce foil distortion during firing.

The platinum foil technique is multifaceted and time consuming and has several disadvantages. For example, it requires an exacting tooth preparation -- the labial shoulder must definitely be smooth to facilitate adaptation of the foil. It also requires a second working die to which the foil must be readapted after each porcelain firing. Since the foil matrix is not removed until after porcelain glazing, there is a lack of direct visualization of the facial margin during contouring. However, the platinum foil technique has been used for years with excellent results and many consider it the standard to which other techniques should be compared (Prince and Donovan, 1983; Dykema et al., 1986).

2. Refractory Die Technique

The second technique fires porcelain directly on a refractory die material, which can withstand the high heat needed to fire porcelain. Avoiding the need for a second die and firing the porcelain margin material directly on the refractory die was an attempt to improve marginal fit and adaptation (Vickery et al., 1969; Southan and Jorgensen, 1972a).

Sozio (1977) and Sozio and Riley (1977) applied a metal ceramic

coating agent composed of a suspension of powdered gold and ceramic materials directly to the die shoulder. When fired, the coating agent adhered to the refractory die, forming a thin film over the shoulder. They theorized that the silica ceramic component of the refractory die material and the ceramic elements of the coating agent adhered to one another. The metal ceramic coating agent formed a temporary bond between the refractory die and the porcelain, and it was believed this caused the porcelain to contract toward the die.

Schneider et al. (1976) also obtained an acceptable marginal fit (38.8 micrometers) of crowns using the refractory die system. But they also reported significant weakness in this technique. For example, the margins of all their crowns were rough and uneven because the porcelain literally stuck to the dies upon firing. Also the die material itself often cracked in bulky areas after only one or two firings. Prince and Donovan (1983) later confirmed these findings and added that the lack of a color difference between the refractory die material and the body porcelain made it difficult to visualize the margin during contouring.

3. Direct-Lift Technique

To overcome the many shortcomings of both the platinum foil and refractory die techniques and to simplify the procedure of porcelain margin fabrication, the direct-lift technique was developed. With this method dental porcelain is condensed directly on the lubricated shoulder of the master die. The crown is then removed from the die and the restoration is fired without the benefit of a supporting matrix (Toogood and Archibald, 1978).

Toogood and Archibald (1978) advocated forming the porcelain labial

margin after the crown had been built and fired to full contour. In contrast, Vryonis (1979) advocated forming the margin initially in opaque porcelain, and then completing the crown build-up in a normal fashion. He recommended a final margin correction with a mixture of three parts body porcelain to one part correction powder.

McLean (1980) also formed the margin first, but used a combination of 1/3 aluminous core porcelain to 2/3 conventional opaque porcelain. He contended such a mixture formed a margin with a decreased pyroplastic flow and a reduced tendency to round during firing.

In evaluating the direct-lift technique, Prince and Donovan (1983) found that porcelain may get under the casting and prevent the crown from seating completely after firing. Also, adapting porcelain into small marginal discrepancies is difficult, and, more importantly, porcelain tends to stick to the die during lift off despite the use of lubricants.

However, the direct-lift technique was quick and simple so researchers experimented to correct these few shortcomings. Manufacturers developed special porcelains specifically for the shoulder-margin area. One major advantage of these high-fusing shoulder porcelains is that they are more stable during firing than conventional body porcelains and thus maintain their marginal configuration (Claus, 1984; Lindke, 1988).

Prince et al. (1983) suggested mixing wax with the porcelain powder instead of either distilled water or modeling liquid. This porcelain-wax mixture is heated and flowed onto the shoulder. Incorporating wax was believed to make the porcelain easier to handle and to lift off the die. They recommended a porcelain to wax ratio of 6:1 by weight. Rinn (1985) and Wiley et al. (1986) also experimented with the wax technique but recommended a porcelain to wax ratio of 8:1. Schrader et al. (1986) showed that the

porcelain:wax mixture underwent significantly less volumeric firing shrinkage than the conventional porcelain:modeling liquid mixture. Gordner (1985) confirmed this finding but explained that the decreased porcelain shrinkage was at the expense of increased porcelain porosity. He cautioned the use of the wax technique, but if used also recommended a porcelain to wax ratio of 6:1. Cooney et al. (1985) and Belles (1987) included the porcelain wax technique in their evaluations of porcelain labial margin fit. Both studies independently concluded that the porcelain-wax method produced a poor marginal adaptation to the die shoulder.

Pinnell and Latta (1987) used a visible light-cured bonding resin as a vehicle for the porcelain powder. A 40% microfilled light-activated bonding resin is added to the porcelain powder until a workable consistency is achieved. Jacobi and Brooks (1988) advocated using a porcelain:resin mix to correct deficient porcelain margins intraorally. Salvo (1990) even introduced a technique of using the visible light-activated resin-porcelain mixture to condense the entire shoulder directly in the mouth. A hand-held visible light sets the mix so it can be removed and fired in a porcelain oven. Once satisfied with the porcelain margin, the body porcelain is applied and contoured on the die in the laboratory before it is fired.

Edge and Maccarone (1987) used a high-heat casting investment liquid, an aqueous sodium silicate solution, as the liquid medium for mixing the margin porcelain powder.

Hinrichs et al. (1990) compared density and tensile strength of unmodified and modified porcelains used for porcelain labial margins. The methods of porcelain modification included wax, light-cured resin, and sodium silicate solution as vehicles for the porcelain powder. Although these modifications made it easier to manipulate the porcelain, the densities and

tensile strengths of the modified porcelains once fired were significantly lower than those of the unmodified porcelain. Hinrichs advised limiting these modified procelains to final bakes for correcting small, troublesome labiogingival discrepancies.

Although the porcelain labial margins can be fabricated by any of the three techniques discussed, the refractory die technique is least favored because the materials are friable and difficult to work with (Prince and Donovan, 1983). Current textbooks favor either the platinum foil or direct-lift technique (Yamamoto, 1985; Rosenstiel et al., 1988).

G. Rounding of Porcelain Margins

The porcelain labial margin metal ceramic crown has become a popular option when treatment planning full coverage restorations. Lacy (1982) has listed several advantages of having the labial margin restored in porcelain:

1) it eliminates unsightly exposed metal at the gingival margin
2) it improves porcelain esthetics in the gingival region by maintaining a significant thickness of porcelain at the margin
3) it avoids the necessity for subgingival preparation which may result in tissue inflammation and subsequent recession
4) it facilitates the establishment of periodontally compatible gingival contours by eliminating the need to overcontour the porcelain to achieve minimum bulk

As mentioned previously, the platinum foil technique has been used for many years and is considered the standard to which other techniques are compared (Prince and Donovan, 1983; Dykema et al., 1986). This technique will produce both an acceptable marginal opening and a sharp porcelain labial

margin (Cooney et al., 1985; West et al., 1985). However, using platinum foil is time consuming and necessitates the added expense of the foil and a spotwelding machine.

In comparison, the direct-lift technique was developed as a quick and inexpensive alternative. However, Hunt et al. (1978) reported that the direct-lift technique produced a rounded porcelain labial margin in cross section. This change in external contour, from a sharp tooth preparation to a rounded restoration margin, results in a less than ideal axial contour and an unwanted gap at the gingival margin. Eissmann et al. (1971) stated that a margin must form the smoothest possible transition from tooth surface to restoration. Any gap at this tooth-restoration junction can accumulate food debris, bacteria, and plaque and lead to deterioration of nearby gingival tissues.

Studies by Cooney et al. (1985), West et al. (1985), and Belles (1987) confirmed that the direct-lift technique produced a rounded porcelain labial margin. Belles noted that the rounding occurred over the external 100 micrometers of the shoulder. All these investigators reported this rounding effect of the porcelain labial margin produced by the direct-lift technique, but they did not measure it in their investigations. In fact, there is no reference in the dental literature to measuring the marginal rounding of the porcelain labial margin. Yet, the sharpness or lack of sharpness of a porcelain margin is critical to the clinical success of this restoration.

The basis for the porcelain rounding is found in an examination of the surface tension of the porcelain particles. In practice the porcelain is condensed to a sharp margin, but when fired the surface tension of the particles fusing produce cohesive forces that are directed inward, reducing the surface area by transforming this sharp margin into a sphere (Craig,

1989). Without a matrix to provide a countering interfacial tension, the porcelain's cohesive forces go unchecked producing a rounded porcelain margin.

Manufacturers answered with the development of "higher fusing shoulder porcelains" that were more stable during firing. The cohesive forces of these porcelains remain inactive at the maximum firing temperatures (Claus, 1984). Arnold and Aquilino (1988) reported that these porcelains did possess a sharper edge, but did not measure it.

Recently a new material for fabricating porcelain labial margins by the direct-lift technique was developed. Vita SM 90 Thermoplastic Shoulder Porcelain combines a special binder with the porcelain (Lindke, 1988), and according to the manufacturer the SM 90 shoulder porcelain does not round during firing. Unfortunately since its introduction in 1988, there have been no independent assessments published in the dental literature.

The objective of this study is to evaluate the accuracy of the high-fusing shoulder porcelains using the direct-lift technique to produce a sharp external porcelain labial margin, as compared to the platinum foil technique. The rounding of porcelain margins has been discussed in the dental literature, but never measured. As previously shown, a sharp margin allows for a smooth transition from tooth to restoration, which is critical to the clinical success of the restoration. Therefore, a goal of this study is to develop a technique using computer technology to accurately measure the porcelain margin sharpness. Having a means to quantify the exact configuration of the porcelain margin will yield a more thorough and clinically relevant assessment of the porcelain labial margin.

In addition, this study will evaluate the accuracy of the high-fusing shoulder porcelains using the direct-lift technique to produce an acceptable

marginal opening and a uniform adaptation to the master die shoulder. Because this is a laboratory study marginal adaptation will be evaluated with the completed crowns seated on their respective master dies.

The results of this investigation will aid in determining which porcelain materials and techniques provide the best marginal fit for the porcelain labial margin metal ceramic restoration.

III. METHODS AND MATERIALS

To make the results of this investigation as clinically relevant as possible, specimen preparation and analysis were conducted to most closely approximate clinical procedures and laboratory fabrication methods. To ensure the most precise application of the techniques studied, a stereo microscope (Glenn Vision Master, Ft. Lauderdale, FL) was an essential part of the laboratory armamentarium to assess fit and finish of the restorations (Rinn, 1985; Titus, 1986).

A. Master Die

The maxillary left central incisor ivorine tooth of a typodont (Columbia Dentoform Corp., New York, NY) was prepared for a porcelain labial margin metal ceramic restoration as follows: 1.5 mm two-plane facial reduction with a 90^{o} shoulder finish line, 2 mm incisal reduction, 1 mm remaining axial reduction with a chamfer finish line, and 6^{o} axial taper (Shillingburg et al., 1987). The labial shoulder was hand planed with a chisel, because Zena et al. (1989) showed that porcelain margins fit hand-planed shoulders more accurately than shoulders finished solely with rotary instrumentation.

The prepared tooth was removed from the typodont and impressed with a low viscosity addition silicone impression material (Reprosil, L.D. Caulk Co., Milford, DE). Light body polysulfide rubber base material (Permlastic, Kerr, Romulus, MI) was then injected into this impression and removed intact when set to give a rubber base die. The die was invested in a noncarbon high-heat phosphate-bonded casting investment (Hi-Temp, Whip Mix Corp., Louisville, KY), removed after one hour, and cast in a nickel-chromium-beryllium base metal alloy (Rexillium III, Jeneric/Pentron Inc., Wallingford, CT). After

divesting, finishing, and polishing, a mid-facial dimple was placed 2.5 mm below the margin with a 1/4 round carbide bur. The result was a smooth metal master die from which all specimens were fabricated (Plate 1).

B. Working Dies

Six impressions were made of the metal master die with an addition silicone impression material (Reprosil). Each impression was poured in an ADA certified Type IV dental stone (Silky-Rock, Whip Mix Corp.) following manufacturers' instructions for minimal expansion. Five stone working dies were made from each impression providing a total of thirty specimens. To harden and seal the labial stone margin, a thin layer of cyanoacrylate cement (International Adhesives Corp., Pembroke Park, FL) was applied and the excess immediately blown off with an air syringe according to the technique described by Toogood and Archibald (1978). Ten stone working dies were then randomly assigned to each of the three groups representing the porcelain labial margin fabrication techniques.

C. Metal Copings

To ensure complete seating of the metal castings, two layers of die spacer (Aero-Gloss, Van Nuys, CA) were applied to the stone working dies according to the technique recommended by Eames et al. (1978).

Standardized wax patterns for metal copings were injection molded as described by Dunkin (1972). In this technique a single working die was lubricated (Die-Sep, Penwalt Jelenko Dental Health Products, Armonk, NY) and positioned in the original typodont. A crown was waxed to full contour using a Type II inlay wax (Maves Co., Cleveland, OH), and cut back to a porcelain labial margin metal ceramic coping design (Figure 1). A custom split-mold was

Plate 1. Metal Master Die

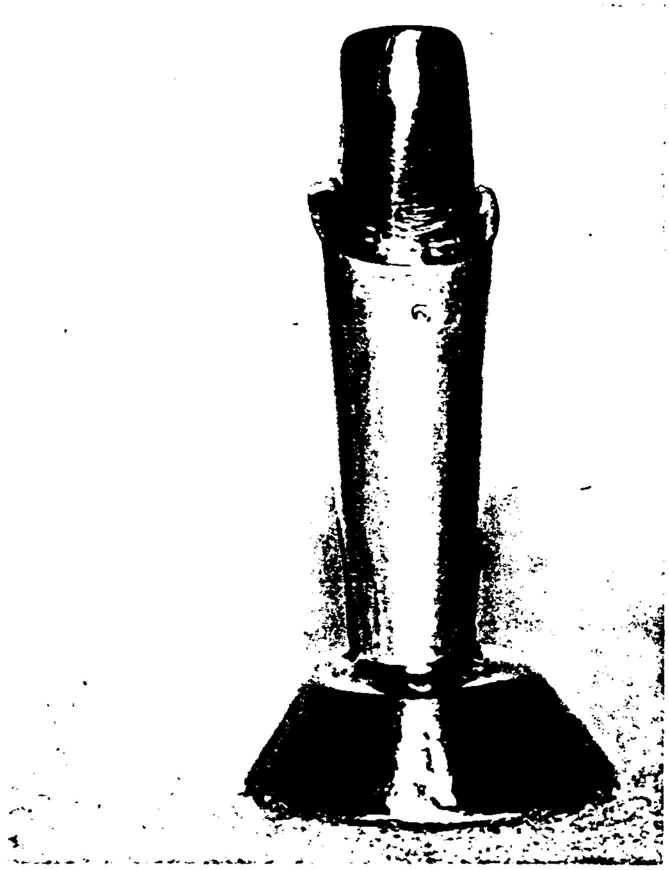
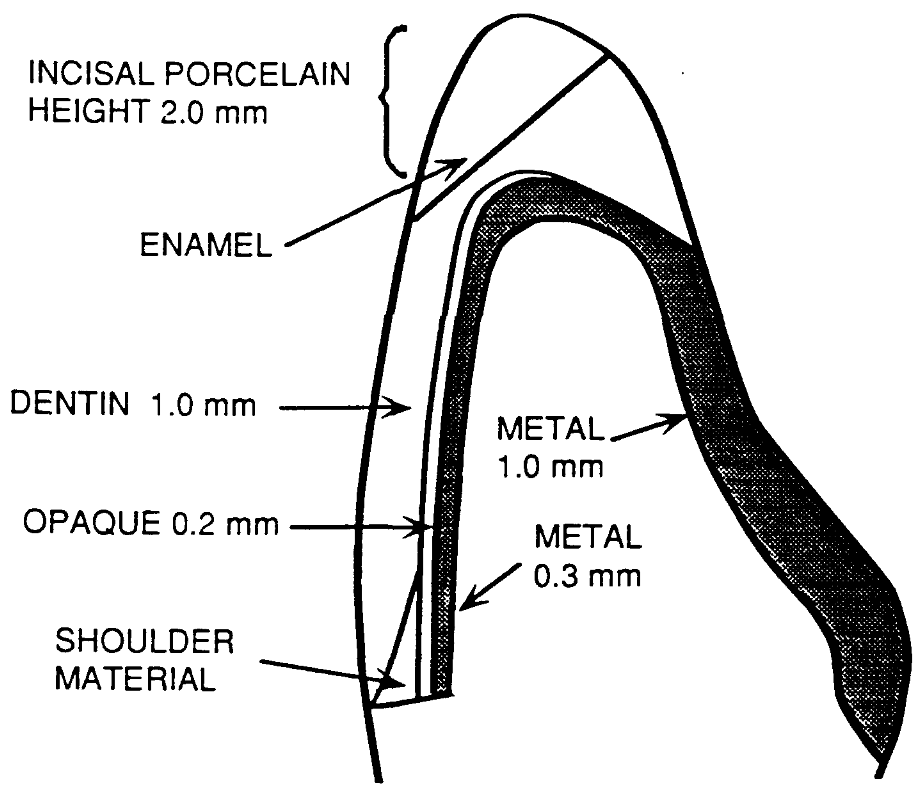


Figure 1. This illustration depicts the porcelain labial margin metal ceramic restoration and the dimensions of its various components.

FIGURE 1. THE PORCELAIN LABIAL MARGIN METAL CERAMIC RESTORATION



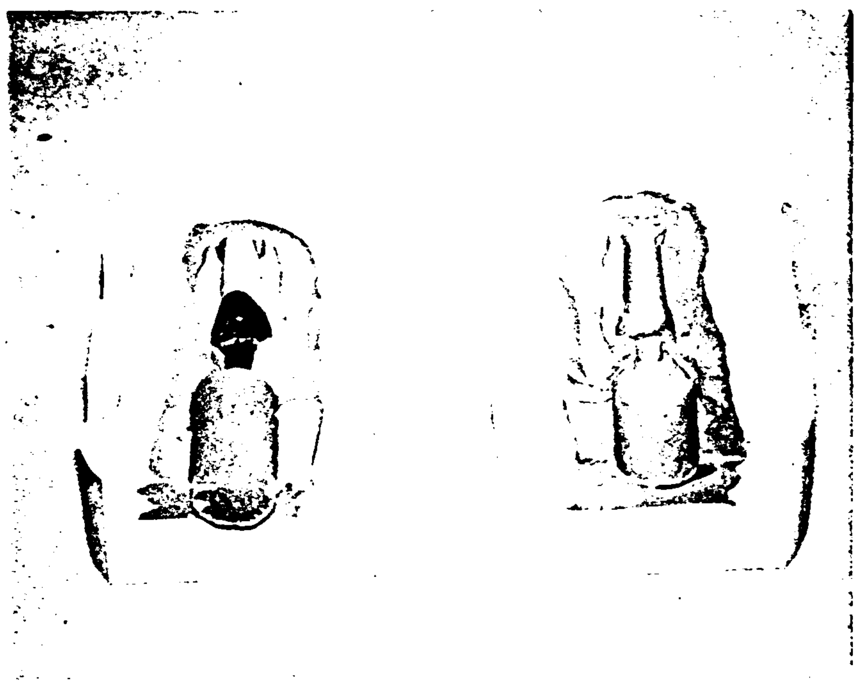
fabricated by impressing this wax coping/die assembly with an addition silicone impression material (Reprosil) reinforced by dental stone (Die-Keen, Columbus Dental, St. Louis, MO) (Plate 2). Subsequent identical wax copings were produced by positioning each stone die in the root portion of the separated split-mold, reassembling the mold, and holding it on the brass fitting of the wax injector pot (Pro-Craft, GFC, Carlstadt, NJ). Molten (120 to 140^{o}F) inlay wax (Maves Co.) was injected into the split mold with one full depression of the plunger. The filled mold was removed from the brass fitting and allowed to bench cool for fifteen minutes. After separating the mold, any wax flash from the seams was removed with a wax carving instrument. The wax margins were finished by hand and the specimen number engraved in the distal-lingual surface. A 3 mm piece of 18 gauge round wax (Kerr, Romulus, MI) was attached to each lingual surface to create a handle to later aid in the fabrication of the restorations.

These wax patterns were invested in a carbon-containing high-heat phosphate bonded investment (Ceramigold, Whip Mix Corp.) and cast in a high noble metal ceramic alloy (Olympia, J.F. Jelenko and Co., Armonk, NY) after wax elimination at 1450^{o}F for one hour. Three wax patterns were sprued in each casting ring.

The metal copings were divested and cleaned, separated from their sprues, and inspected for the presence of internal nodules. Any positive irregularities were removed with a 1/2 round carbide bur. The die spacer was removed with acetone before the metal copings were returned to their respective working dies.

The porcelain bearing metal surfaces were prepared by finishing to a minimum thickness of 0.3 mm with a white finishing stone (Ticonium Co.,

Plate 2. Wax Injection Mold



Albany, NY). The facial metal margin was finished to contact the shoulder at the axio-gingival line angle.

The castings were air-abraded for six seconds with 25 micrometer aluminum oxide particles under 40 psi. The castings were steam cleaned andblown dry with compressed air in preparation for porcelain application (Plate 3).

D. Porcelain Application

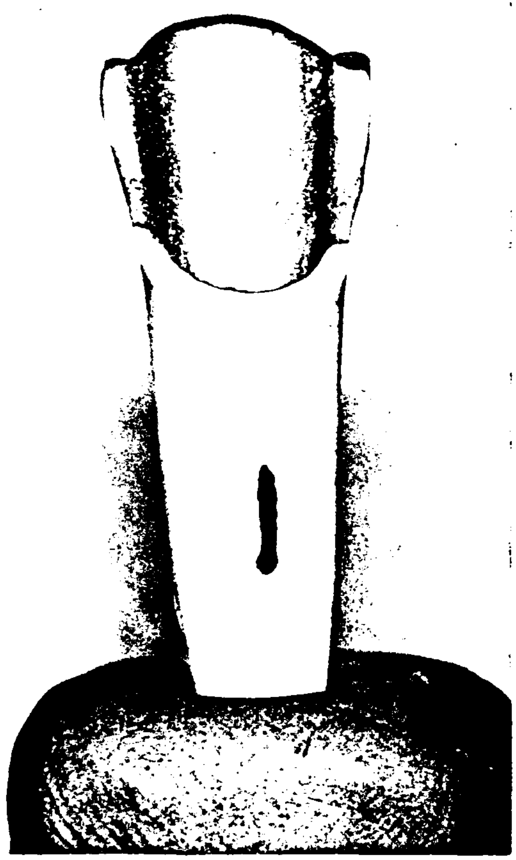
Commercially available Vita VMK 68 porcelains (Vident, Baldwin Park, CA), shade A3, were used for all specimens to eliminate any variation due to the differing oxides between shades.

1. Direct-Lift Technique - Shoulder Porcelain

In a recently calibrated Ultra-Mat CDF porcelain oven (3M/Unitek, Monrovia, CA) the metal copings were oxidized by air firing to 1040°C at a rate of 55°C/minute. They were then air-abraded to remove the oxide layer, steam cleaned, and blown dry with compressed air.

Two layers of Vita VMK 68 opaque porcelain (512, Vident) were applied and fired (first firing at 980°C, second firing at 960°C) as described in the Vita VMK 68 technique manual. The porcelain used to fabricate the shoulder area was a Vita high-fusing shoulder porcelain (595, Vident) specifically designed to reduce shrinkage (Claus, 1984). VMK 68 modeling liquid (Vident) was used as the liquid medium. A lubricating film (Ceramic Separating Pen, Williams Dental Co., Amherst, NY) was applied to the shoulder area of each stone working die to facilitate removal of the condensed porcelain.

Plate 3. Metal Casting Seated on Stone Die



Each coping was returned to its working die and the shoulder porcelain applied. The initial increment of porcelain was placed only on the shoulder and rolled 2 to 3 mm onto the opaqued axial surface. The porcelain was condensed with vibration and dried with a tissue to remove excess moisture. An ultrasonic porcelain condenser (Ceramosonic Condenser, Shofu Dental Corp., Menlo Park, CA) was used to standardize the condensation procedure. Vibration condensation has been shown to produce the most uniform structure, fewest voids, and the highest strength of the various condensation techniques (Gill, 1932; Yamamoto, 1985). The dry porcelain was carved to a sloping configuration from the axial wall to the shoulder margin and smoothed with a dry brush. This eliminated unnecessary bulk at the margin and ensured adequate fusing with the opaque layer. The coping was carefully lifted off the die by first rotating the coping slightly, then lifting up and out. The specimen was then placed on a sagger tray, dried thoroughly, and fired under vacuum to 950^{o}C with a one-minute hold time.

When the coping was returned to its die after the first firing, a slight marginal opening was visible. To correct this marginal discrepancy, the shoulder of the die was relubricated and a small amount of porcelain was placed on the inferior aspect of the previously fired shoulder. The crown was then returned to the die and ultrasonically vibrated until it was completely seated. Porcelain was added from the labial to any open margin areas, condensed, and smoothed as before. The coping was again carefully removed and vacuum fired to 950^{o}C with a one-minute hold time. A third correction firing at 950^{o}C was completed on each specimen prior to the application of body porcelain.

To reflect clinical relevancy, the body porcelain was applied and contoured with the coping/die assembly seated in the original typodont (Plate 4). As a further check to standardize the amount of body porcelain fired, the first completed restoration was impressed in an addition silicone putty material (Reprosil). This putty impression was sectioned to make two indices: a mesial-distal index and a buccal-lingual index (Plate 5). During condensation and prior to firing, the indices were used to verify that equivalent amounts of body porcelain were applied to each restoration.

Vita VMK 68 body porcelain (542, Vident) was condensed, vibrated,dried, and fired. Two body bakes were completed on each restoration. The first body bake was fired under vacuum at a rate of 55°C/minute to a final temperature of 920°C. The second body buildup was vacuum fired to 915°C. The crown contours were adjusted with fine-grit diamond laboratory burs using a hand-held laboratory handpiece.

A final marginal correction with shoulder porcelain was accomplished at 915°C. The marginal area was contoured and polished using a porcelain adjustment kit (Shofu Dental Corp., Menlo Park, CA). Lastly, the restorations were air fired to a natural glaze at 920°C with a one-minute hold time.

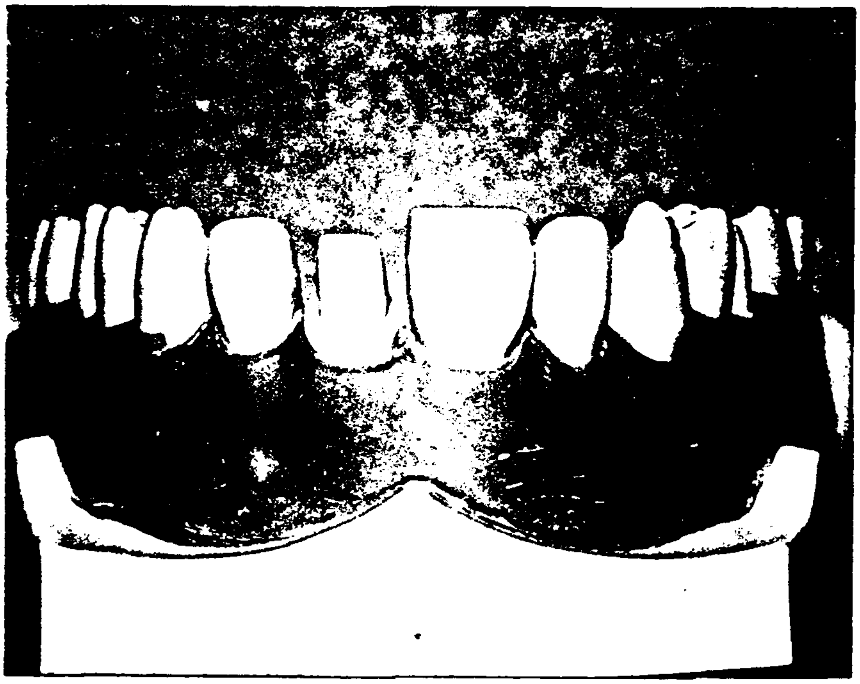
2. Platinum Foil Technique

Using the platinum foil technique requires a second stone working die with no cervical undercut. To fabricate this second die, the facial cervical undercut of the stone (now master) die was blocked out with inlay wax (Maves Co.) where the foil was to be located. Each blocked out master stone die was impressed with an addition silicone material (Reprosil) and poured in an ADA certified Type IV dental stone (Silky-Rock). The resultant stone dies

Plate 4. Typodont to Standardize Body Porcelain

A. Stone Die Positioned in Typodont (upper plate)

B. Completed Crown/Stone Die Positioned in Typodont (lower plate)



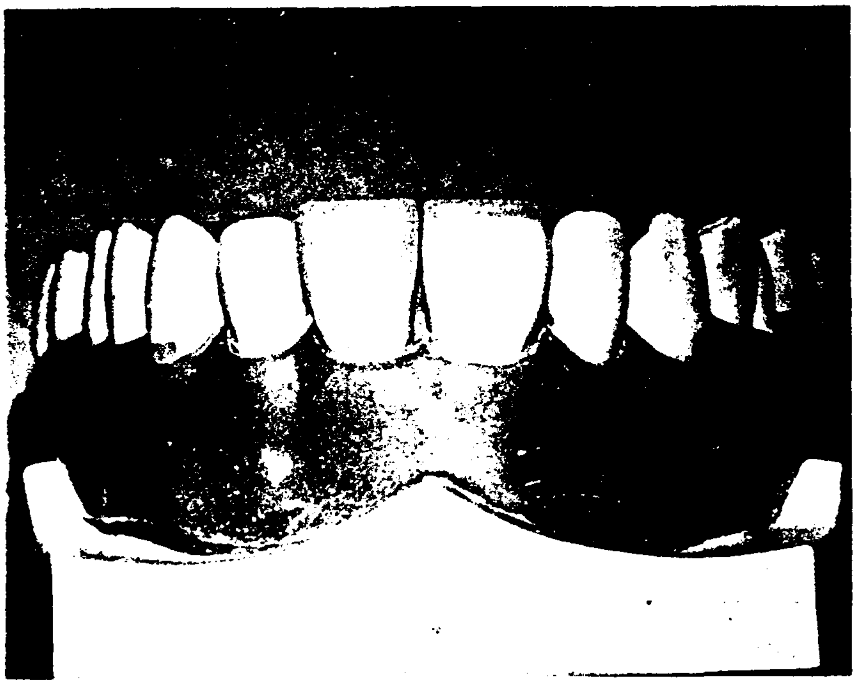
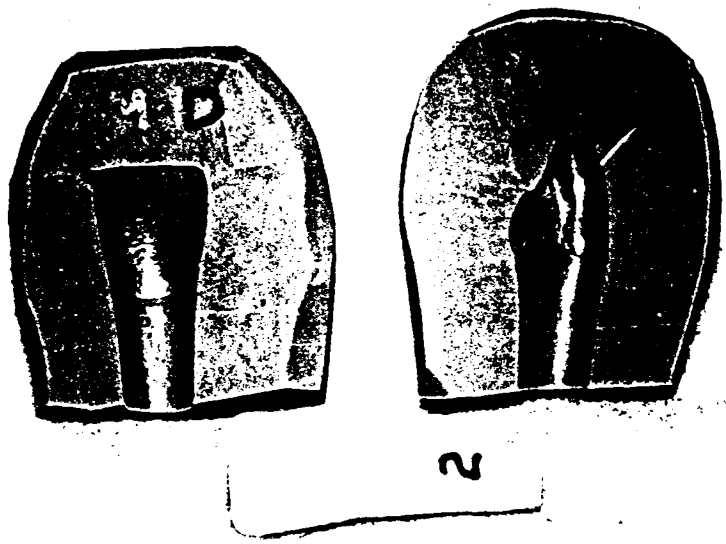


Plate 5. Addition Silicone Putty Indices to Standardize Body Porcelain


4D

served as the working dies on which the restorations were built. A thin layer of cyanoacrylate cement (International Adhesives Corp.) was applied to the labial margin of each stone die as described previously.

A piece of platinum foil, 0.001 inch in thickness (Baker Dental, Engelhard Industries Division, Carteret, NJ) was heated in a flame to remove surface contaminants and anneal it. The foil was intimately adapted to the cervical half of the facial surface of the die with a wooden instrument made from a standard cotton tipped applicator. The foil extended apically 2 mm beyond the shoulder and 2 to 3 mm incisally along the axial wall of the die. To ensure full seating of the metal coping, it was necessary to relieve the die slightly in the region where the platinum foil and the coping overlapped (Goodacre et al., 1977). The foil was secured to the casting on the die with sticky wax (Moyco Industries Inc., Philadelphia, PA). The casting with the foil in place was carefully removed from the die and placed in a spotwelder.

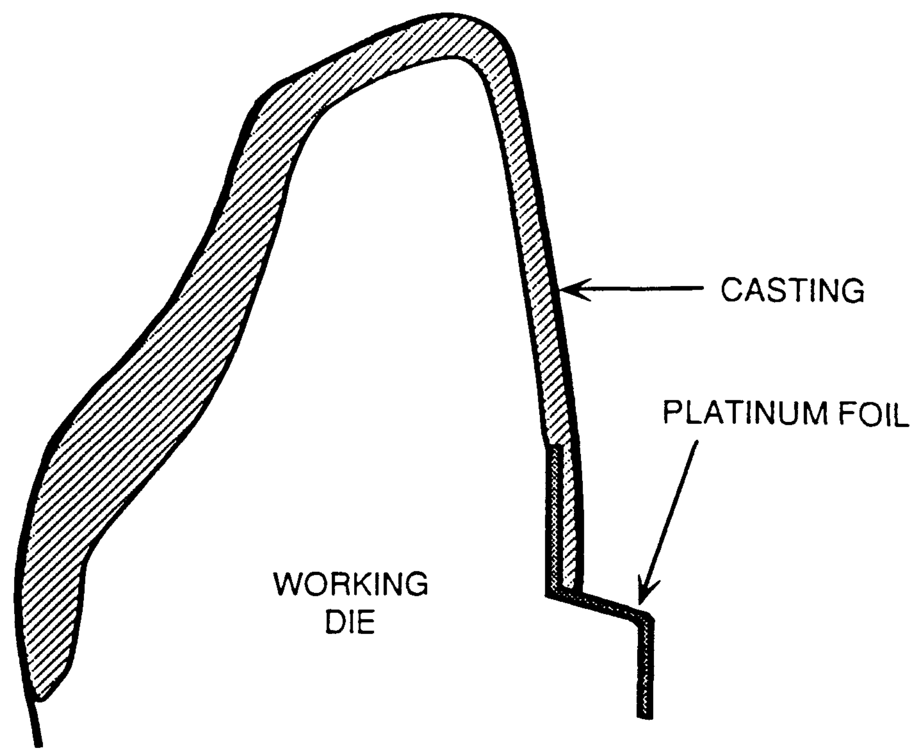
The platinum foil was welded to the casting at three locations approximately 1.5 to 2 mm apart using an orthodontic spotwelder (Rocky Mountain Associates International Inc., Denver, CO). The heat selector control of the spotwelder was placed on the heavy setting (No. 4) and a delivery of three impulses produced a sufficiently strong spot weld (Figure 2). The casting and foil were air-abraded, steam cleaned, and blown dry with compressed air.

The metal coping and foil were oxidized by air firing to 1040°C at a rate of 55°C/minute. They were again air-abraded, steam cleaned, and blown dry.

The Vita VMK 68 opaque porcelain (512, Vident) was applied so that it masked the metal ceramic alloy but did not extend onto the platinum foil

Figure 2. This illustration shows the location of the platinum foil spot welded to the casting. The stone working die should have no facial cervical undercut so that the adapted foil does not distort when the casting is removed from the die.

FIGURE 2 : PLATINUM FOIL SPOT WELDED TO CASTING



matrix. Two layers of opaque porcelain were applied and fired (980°C, 960°C) as previously described for the direct-lift technique.

The casting was returned to the die and the foil readapted to the shoulder prior to the placement of body porcelain. To standardize crown contours and the amount of body porcelain fired, the porcelain was built in the typodont and checked with the putty indices as previously described.

The Vita VMK 68 body porcelain (542, Vident) was built to contour using the condensation, vibration, and drying techniques previously described. A ditch was then created between the platinum foil and the porcelain with a No. 11 scalpel blade (Beaver, Waltham, MA). The ditch extended the width of the shoulder to prevent porcelain shrinkage from distorting the foil matrix. The build-up was fired under vacuum at a rate of 55°C/minute to a final temperature of 930°C. The fired restoration was returned to the die and the platinum foil readapted to the labial margin. Porcelain was condensed in the cervical ditch and fired a second time to 925°C. A third firing (920°C) was necessary to completely fill the cervical ditch.

The restoration was placed on the die for contouring and finishing. All adjustments were performed with fine-grit laboratory diamonds and the Shofu porcelain adjustment kit (Shofu Dental Corp.). Finishing included the elimination of all porcelain and platinum foil extending cervically beyond the margin of the shoulder.

Lastly, the restorations were fired to 930°C with a one minute hold in air to achieve a natural glaze. After glazing, the platinum foil was removed and the restorations fitted on their respective stone master dies.

3. Direct-Lift Technique - SM 90 Porcelain

The SM 90 Thermoplastic Shoulder Porcelain compounds (Vident, Baldwin Park, CA) are comprised of VMK 68N shoulder porcelain containing a special binder which provides thermoplastic properties (Lindke, 1988). Primary compound (red tab) is used to form the porcelain margin initially, and secondary compound (white tab) is used to correct marginal discrepancies observed after the body build-up.

The metal copings were oxidized and opaqued as previously described for the direct-lift technique. A lubricating film (Williams Dental Co.) was applied to the shoulder area of each stone working die to facilitate removal of the shoulder porcelain. Each coping was seated on its individual working die and the SM 90 porcelain applied using an electric waxing spatula (Micromatic, Belle de St. Claire, Chatsworth, CA) to control heating of the material. A small quantity of primary compound (red tab) was picked up with the warm metal instrument and wiped onto the die shoulder. The porcelain was then condensed with pressure from the electric spatula tip. Using this method, the entire shoulder area was built with primary compound to a sloping configuration from the axial wall to the shoulder margin. Any excess bulk or compound extending past the margin was removed with a glass spatula (Vident). The coping was separated from the die, placed on a sagger tray, and fired under vacuum to 950^{o}C with a one-minute hold time.

Once fired and returned to the die, a slight marginal opening was visible. To correct this opening, the shoulder of the die was relubricated and small increments of warm primary compound were wiped and condensed into the marginal opening with pressure from the facial. The coping was then

removed from the die and fired to 950°C. A pilot study revealed that the SM 90 porcelain material was too viscous and hardened too quickly to permit correction by placing porcelain on the inferior aspect of the previously fired porcelain shoulder and returning the coping to the die. The coping was never able to be completely reseated. This reseating technique is best utilized with a mix of wet porcelain.

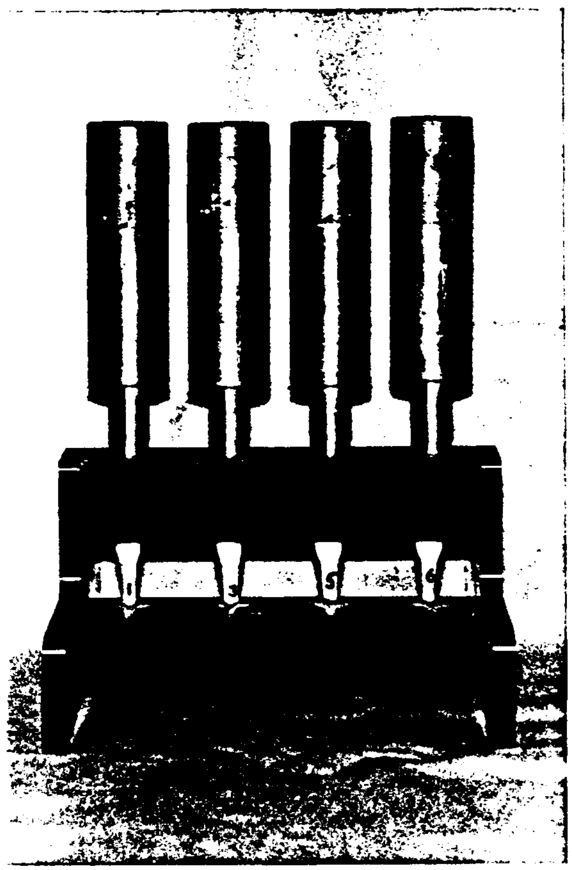
The body porcelain was applied in exactly the same manner as used for the direct-lift technique.

The final marginal correction was accomplished with secondary compound (white tab), which has a lower firing temperature and greater flow properties. The warm secondary compound was wiped and pressed into the remaining marginal gap with the wax spatula. Before firing, the secondary compound had stresses relieved by wiping the margin with an acetone saturated cotton pellet. The coping was removed from the die and glazed naturally at 920°C with a one-minute hold time in air.

E. Specimen Luting

The finished restorations were luted to their individual stone dies with an autopolymerizing unfilled resin (Concise Orthodontic Bonding System, Dental Products/3M, St. Paul, MN). This Bis-GMA resin bonding agent was mixed according to manufacturers' instructions and a thin layer was applied to the incisal edge of each die. The restorations were individually seated with firm finger pressure and immediately placed under a 400 gm static load for five minutes according to Brukl and Philip (1987) (Plate 6). At this point, the specimens were ready for the first set of measurements.

Plate 6. Static Load Apparatus



F. Facial Measurements

The facial marginal opening of each specimen was measured with a Unitron Universal Measuring Microscope (Unitron Instruments Inc., Plainview, NY). The measurement location along the facial crown/die interface was standardized by using the dimple index in the stone die (Figure 3). A pilot study revealed that the diameter of the dimple in stone was approximately 660 micrometers. At x30 power, both the dimple and the margin remained in view. The crosshairs of the microscope were positioned on the left vertical tangent of the dimple. The magnification was increased to x100 and the stage was moved to focus only on the marginal opening. The horizontal positioning of the crosshairs did not change. Measuring Position #1 was where the vertical crosshair intersected the margin. The stage was then moved 330 micrometers to the right to measuring Position #2, and again 330 micrometers to measuring Position #3. Three measurements of the marginal gap were made at each of the three measuring positions. These three measurements were averaged to yield a mean marginal opening (micrometers) for each specimen.

G. Specimen Preparation

The specimens were prepared for the embedding procedure by first securing them with sticky wax (Moyco Industries, Philadelphia, PA) to a 2 mm thick plastic sheet (Splint Biocryl, Great Lakes Orthodontics, Tonawanda, NY). Theplastic sheet had been trimmed to fit inside a large vacuum mixing bowl. There were five sheets with six specimens per sheet for thirty specimens. Matrices for the embedding material were cut (1" x 3/4") from polybutyrate tubing (Plastic Supply of San Antonio, San Antonio, TX), positioned over the specimens, and secured with sticky wax (Moyco Industries) (Plate 7).

Figure 3. This illustration shows how the facial marginal opening was measured.

A. The location was standardized with a dimple placed in the metal master die. At x30 magnification, the crosshairs were positioned on the left vertical tangent of the dimple.

B. The magnification was increased to x100 and the stage moved up to focus only on the marginal opening. Three measurements of the marginal opening were made at each of three positions (#1, #2, #3) along the 660 micrometer distance on the facial margin.

FIGURE 3. FACIAL MEASURING POSITIONS

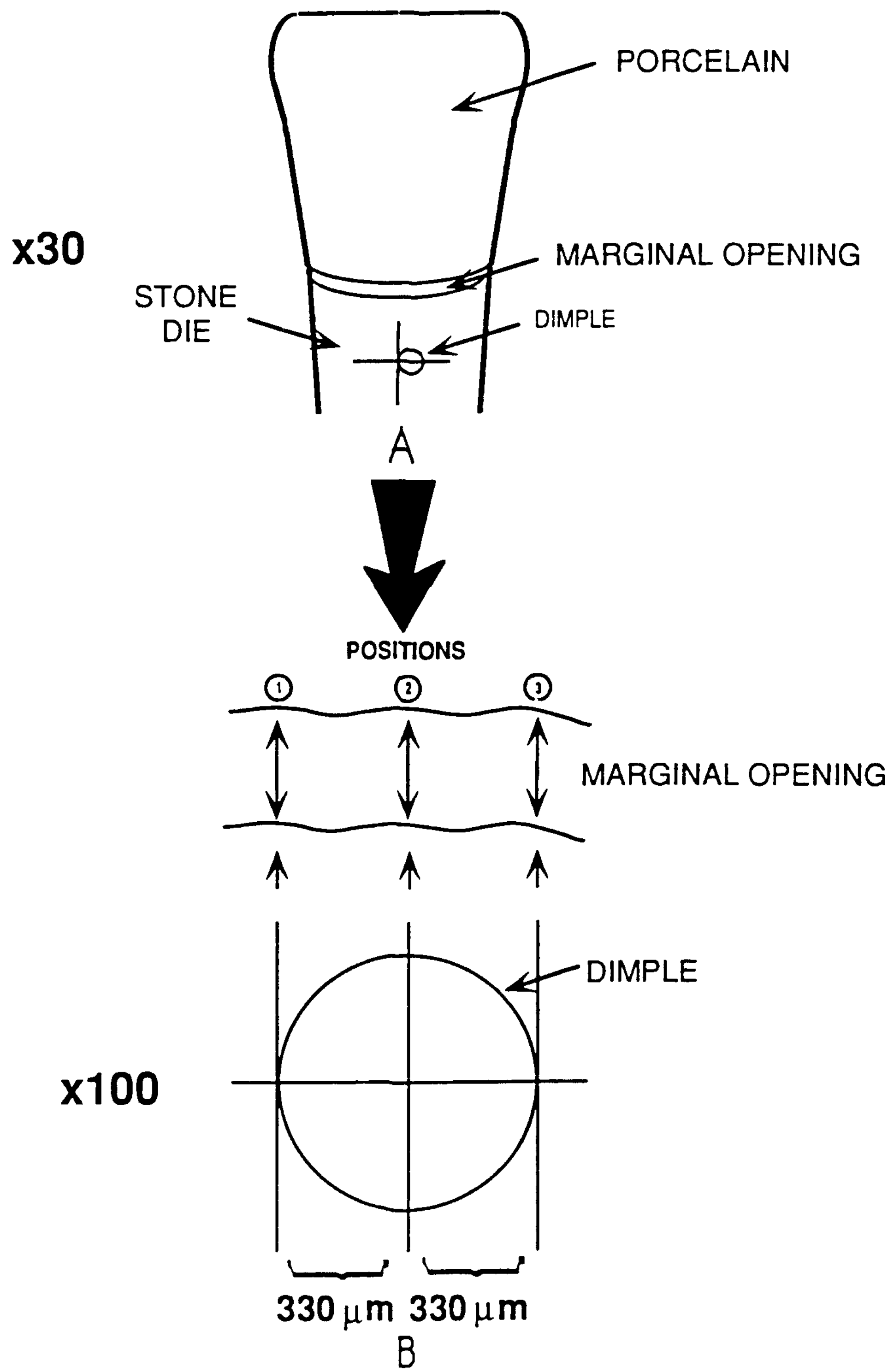
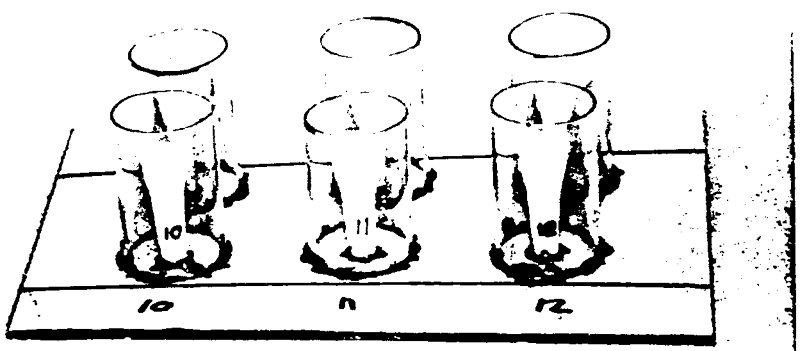


Plate 7. Specimens Ready for Embedding


10
11
12

The specimens were embedded in a clear liquid plastic casting resin (Castin' Craft Clear Plastic Resin, ETI, Fields Landing, CA). The embedding resin was poured into the matrices and the specimens immediately placed under vacuum until all air bubbles had risen to the top (approximately 10 minutes). The resin was allowed to cure for 24 hours.

The embedded specimens were sectioned at the midpoint facial-lingually with an ultra thin diamond disc (Isomet Plus Precision Saw, Buehler Ltd., Lake Bluff, IL) using a 180 gm load and a speed of 700 RPMs. The sectioned specimens were then metallographically polished by successive abrasion on 240 through 600 grit silicon carbide strips (Buehler Ltd.) mounted on a water lubricated Handimet Grinder (Buehler Ltd.). Polishing removed any saw smearing to yield sharply defined interfaces between materials (Plate 8).

H. Cross-Sectional Measurements

The fit of the porcelain to the die shoulder was evaluated according to a technique described by West et al. (1985). The clearer, more defined half of each sectioned specimen was measured. The marginal opening was measured in cross-section using a measuring microscope (Unitron Instruments, Inc.) at x100 magnification. The standardized measuring locations (Figure 4) were as follows: Site X was on the shoulder where the initial effects of marginal rounding were detected, Site Z was at the point on the die shoulder directly below the metal-porcelain interface, Site Y was the midpoint between Site X and Site Z. In addition, to further quantify any uneven shoulder adaptation the highest and lowest point were also measured. Three measurements were made at each site and averaged to yield the marginal opening of that particular site.

Plate 8. Sectioned Specimen

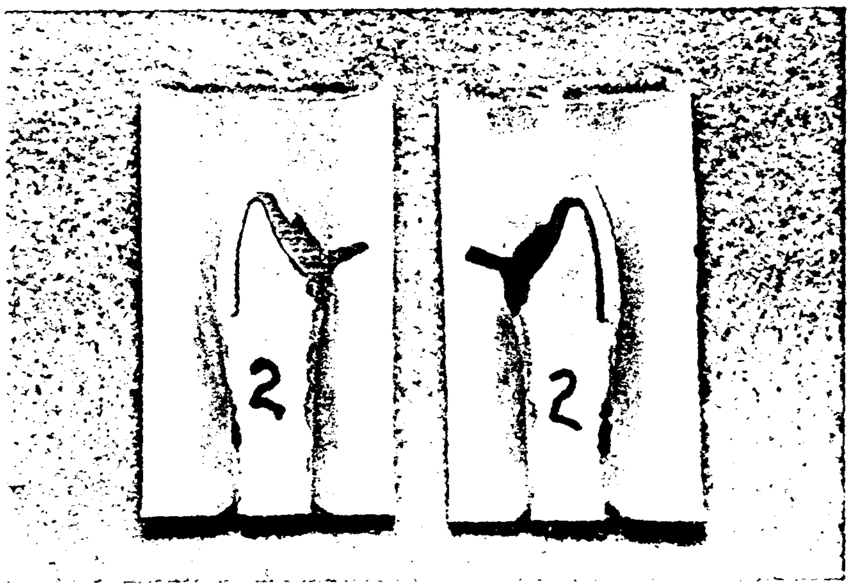
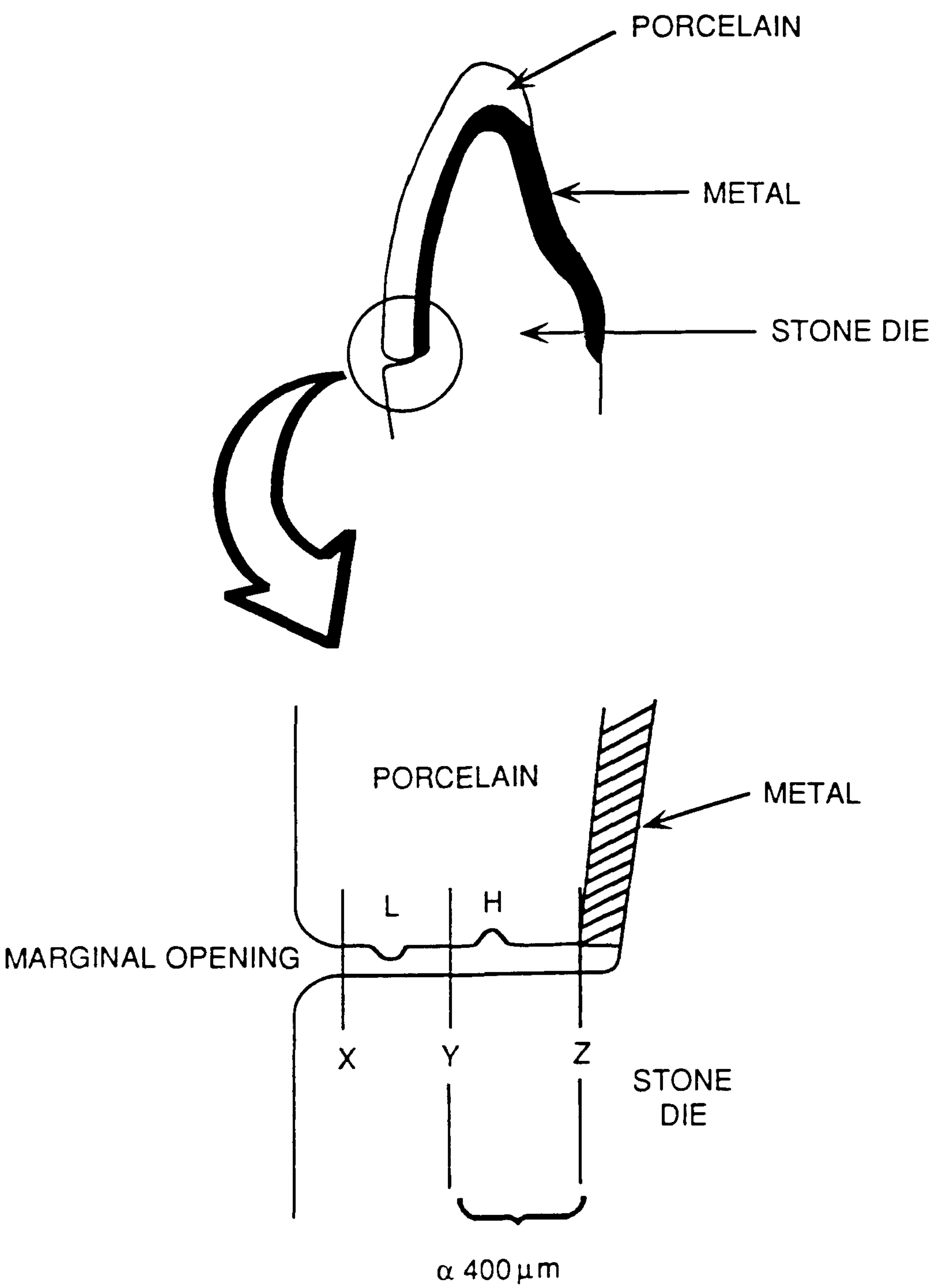

2
2

Figure 4. This ilustration shows the cross-section marginal opening measuring sites. The standardized measuring locations were: Site X was the point on the shoulder where the first effects of marginal rounding were detected; Site Z was at the point on the die shoulder directly below the metal-porcelain interface; Site Y was the midpoint between Site X and Site Z. The highest (H) and lowest (L) points were also measured.

FIGURE 4. CROSS SECTION MEASURING SITES



The amount of porcelain rounding that occurred during fabrication was measured from black and white photographs of the sectioned specimens. The specimens were photographed at x40 magnification using a standardized photographing microscope (Nikon UFX-II, Tokyo, Japan) and black and white print film (TMX-135, Eastman Kodak Co., Rochester, NY). A contact print sheet was developed to maintain specimen sequencing. From the negatives, 5 x 7 inch standardized prints were developed using an Omega Pro Lad Enlarger (Berkey Marketing Co. Inc., Woodside, NY) and a constant lens to easel distance of 31 centimeters.

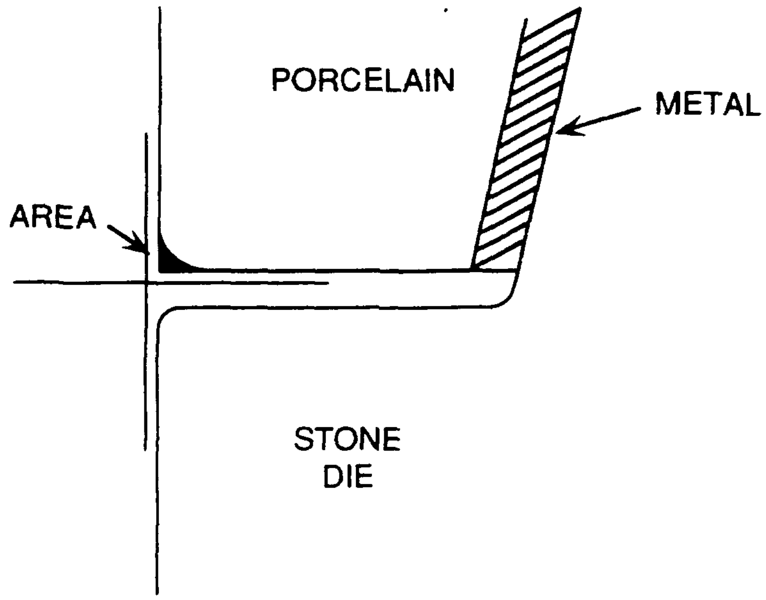
The 5 x 7 inch black and white prints were then scanned (Microtek Image Scanner, Torrance, CA) into a computer (MacIntosh II, Apple Computer Inc., Cupertino, CA) for measuring. Each specimen image was brought up on the screen and straight lines superimposed along the facial plane (Y-axis) and shoulder porcelain plane (X-axis) (Figure 5) (Plate 9). The intersection of these two lines indicated the theoretical sharp porcelain margin -- the margin that would be seen if porcelain rounding did not occur. A third line was then superimposed over the actual porcelain margin that was observed (Plate 10). The area bordered by these three lines represented the extent of porcelain rounding that had occurred. The area of this triangle was calculated by the computer program (MacDraft, Innovative Data Design, Inc., Cupertino, CA) (Plate 11). Since the area reported is calculated from an enlarged photograph, it is a larger value than actually exists. However, measuring the area of standardized enlargements yielded numbers that provided a more exacting relative comparison among fabrication techniques than previous methods (Brockhurst et al., 1983; Bessing, 1986).

Figure 5. This illustration shows how the amount of porcelain rounding was measured.

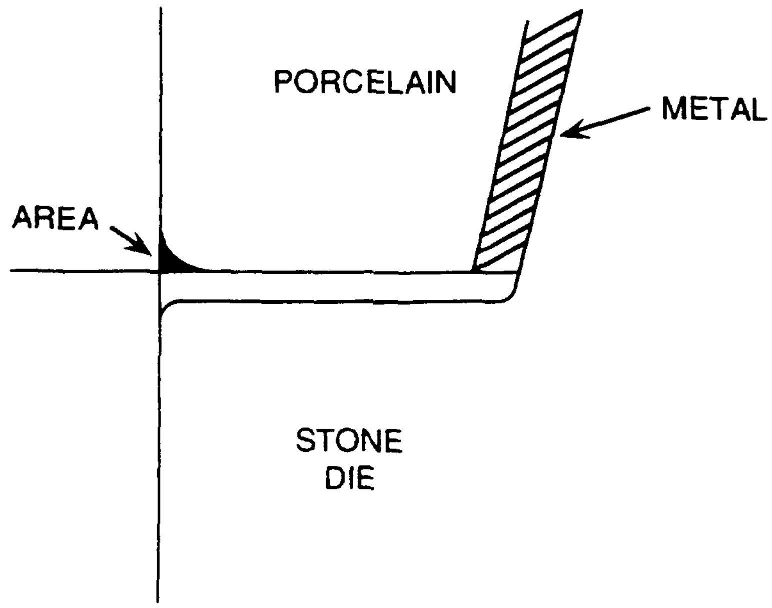
A. Straight lines were superimposed on the facial (vertical) and shoulder porcelain (horizontal) axes. The intersection of these two lines would represent the theoretical sharp porcelain margin.

B. The area bordered by these lines and the actual porcelain margin represented the amount of porcelain rounding that occurred.

FIGURE 5. MEASURING PORCELAIN ROUNDING



A



B

Plate 9. Specimen Image on Computer Screen with Straight Lines Superimposed Along the Facial Plane (Y-Axis) and the Shoulder Porcelain Plane (X-Axis)

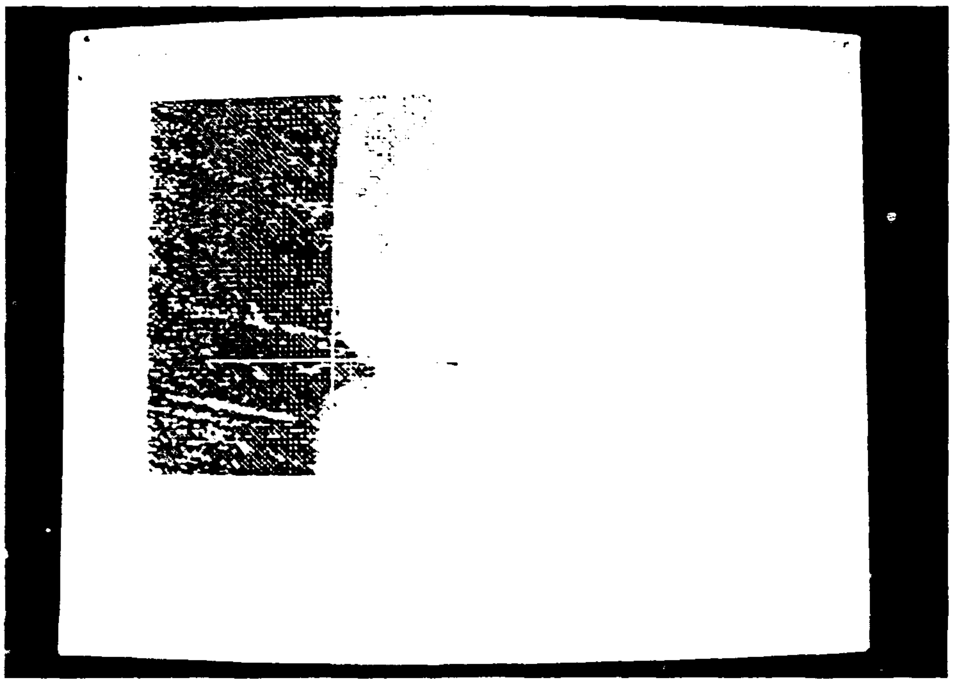


Plate 10. Specimen Image on Computer Screen with the Third Line Being Superimposed Over the Actual Porcelain Margin

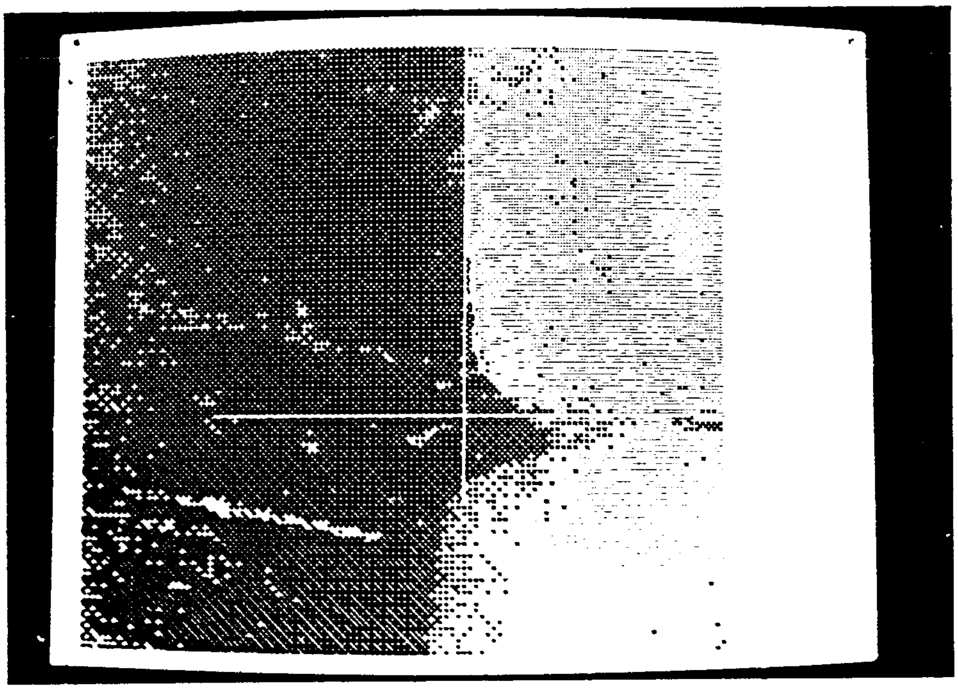
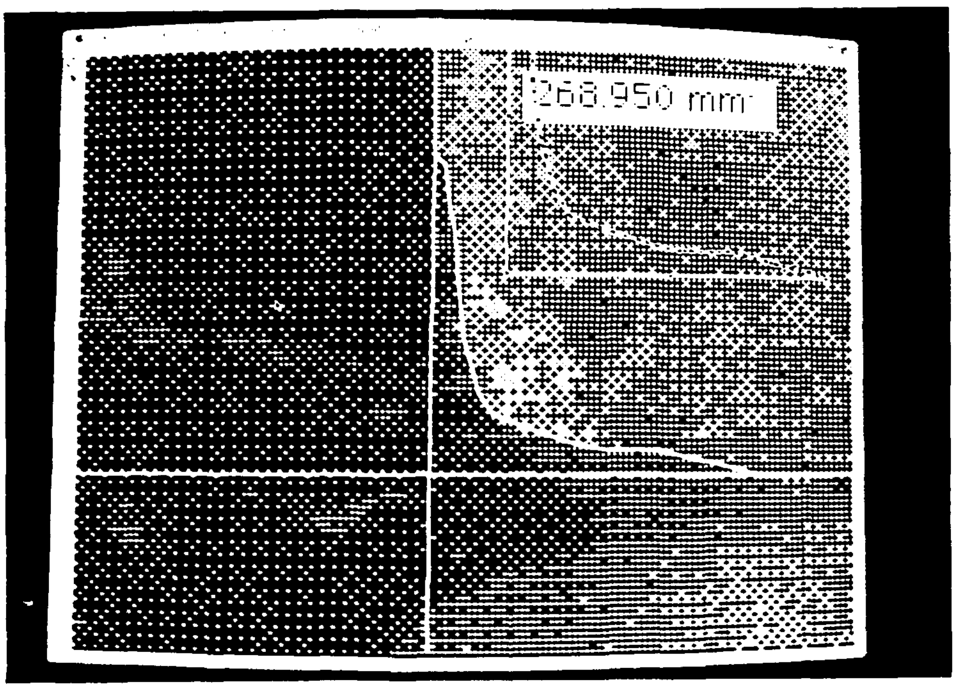


Plate 11. Specimen Image on Computer Screen with the Area of Porcelain Rounding Calculated


268.950 mm

During the measuring, it was noted that the rounding of some specimen margins followed the rounding of the stone die and actually went below the horizontal plane of the porcelain shoulder (Figure 6). These specimens were deemed to have a positive rounding (+). Those specimens that rounded above the horizontal plane of the porcelain shoulder were reported as having a negative rounding value (-) (Figure 6).

I. Statistical Analysis

The mean distances and standard deviations were determined for each of the three porcelain labial margin fabrication techniques at nine measurement sites: (1) facial margin; (2) cross-section Site X; (3) cross-section Site Y; (4) cross-section Site Z; (5) cross-section H value; (6) cross-section L value; (7) cross-section shoulder width (mean of Sites X, Y, Z); (8) cross-section area of rounding; and (9) cross-section area of positive or negative rounding.

A one-way analysis of variance (ANOVA) was used to examine the variation between the technique groups for these nine measurement sites.

This analysis was followed by a Tukey's multiple comparison test to identify significant differences at a $p \leq .05$ level of significance.

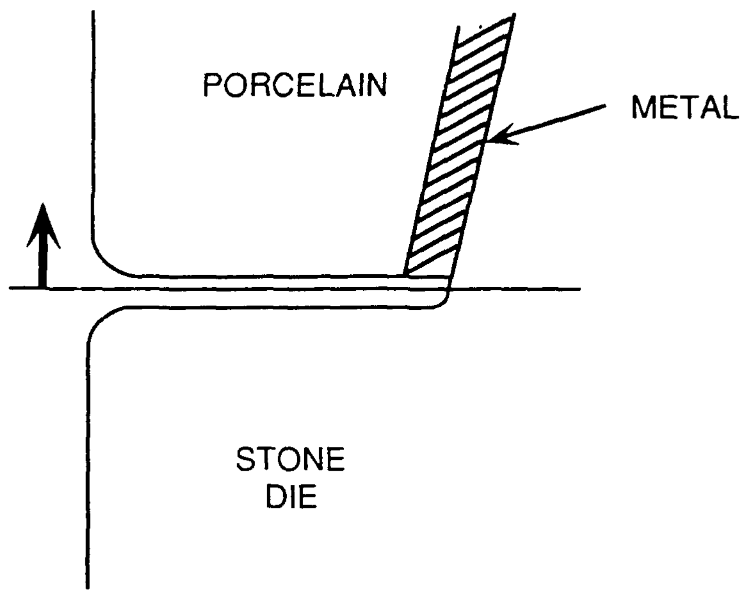
Figure 6. This illustration characterizes the nature of the porcelain rounding.

A. Specimens that rounded above the horizontal plane of the porcelain shoulder were determined to have negative rounding.

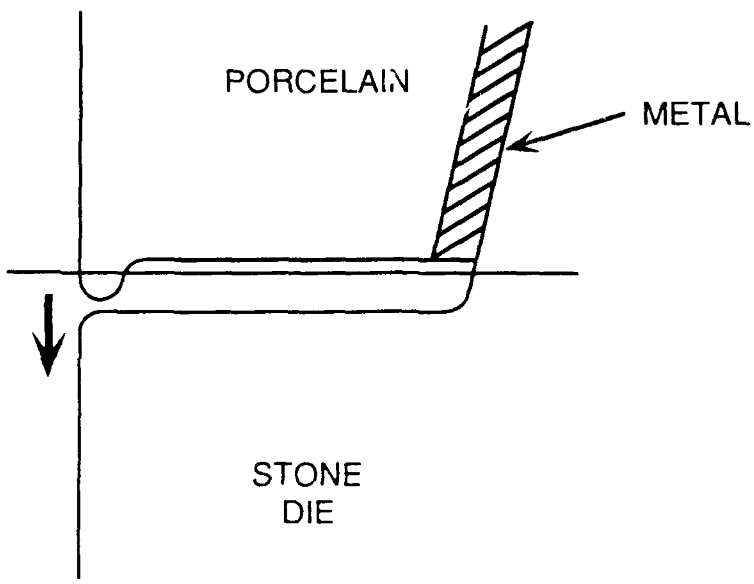
B. Specimens that followed the rounding of the stone die and extended below the horizontal plane of the porcelain shoulder were considered to have positive rounding.

In actuality. the horizontal line is superimposed on the horizontal plane of the porcelain shoulder.

FIGURE 6. NATURE OF PORCELAIN ROUNDING



A. NEGATIVE (-) ROUNDING



B. POSITIVE (+) ROUNDING

IV. RESULTS

All raw data are contained in the Appendix. The means and standard deviations of the: 1) facial margin; 2) cross-section Site X; 3) cross-section Site Y; 4) cross-section Site Z; 5) cross-section H value; 6) cross-section L value; 7) cross-section shoulder width (mean of Sites X, Y, and Z); 8) cross-section area of rounding; and 9) cross-section area of positive or negative rounding are listed in Tables 1, 2, 3, 4, 5, 6, 7, 8, and 9 respectively.

A one-way analysis of variance (ANOVA) was used to examine the variation between the technique groups of the nine measurement sites ($p \leq .05$) (Tables 10 through 19). This analysis was followed by a Tukey's B-procedure multiple comparison test to identify significant differences at a $p \leq .05$ level of significance (Tables 20 through 23).

A. Facial Margin

The facial marginal openings of the platinum foil technique group (13.7 $\pm$4.6 micrometers) were significantly larger than either the direct-lift technique group using high-fusing shoulder porcelain (8.2 $\pm$2.0 micrometers) or the direct-lift technique group using SM 90 porcelain (11.3 $\pm$4.6 micrometers) (Tables 10 and 20). However, the facial marginal openings using high-fusing shoulder porcelain and SM 90 porcelain were not statistically different from one another at this site.

B. Cross-Section Site X

The margi.'al openings at cross-section Site X of the direct-lift technique using high-fusing shoulder porcelain (14.2 $\pm$12.2 micrometers), the

platinum foil technique (20.1 ±9.5 micrometers), and the direct-lift technique using SM 90 porcelain (10.6 ±6.4 micrometers) were not statistically different (Table 11).

C. Cross-Section Site Y

The marginal openings at cross-section Site Y of the direct-lift technique using SM 90 porcelain (134.4 ±50.3 micrometers) were significantly larger than either the platinum foil technique (17.7 ±7.2 micrometers) or the direct-lift technique using high-fusing shoulder porcelain (33.5 ±16.2 micrometers) (Tables 12 and 21). The platinum foil technique and the direct-lift technique using high-fusing shoulder porcelain were not statistically different from one another at this site.

D. Cross-Sect'on Site Z

The marginal openings at cross-section Site Z of the direct-lift technique using high-fusing shoulder porcelain (65.6 ±56.1 micrometers), the platinum foil technique (41.9 ±33.5 micrometers), and the direct-lift technique using SM 90 porcelain (63.8 ±29.6 micrometers) were not statistically different (Table 13).

E. Cross-Section H Value

The marginal openings at the highest point (H) in cross-section of the direct-lift technique using SM 90 porcelain (145.6 ±59.3 micrometers) were significantly larger than either the platinum foil technique (49.9 ±29.4 micrometers) or the direct-lift technique using high-fusing shoulder porcelain (31.4 ±46.6 micrometers) (Tables 14 and 22). The platinum foil technique and

the direct-lift technique using high-fusing shoulder porcelain were not statistically different from one another at this site.

F. Cross-Section L Value

The marginal openings at the lowest point (L) in cross-section of the direct-lift technique using high-fusing shoulder porcelain (6.5 $\pm$2.0 micrometers), the platinum foil technique (9.3$\pm$3.3 micrometers), and the direct-lift technique using SM 90 porcelain (10.3 $\pm$6.5 micrometers) were not statistically different (Table 15).

G. Cross-Section Shoulder Width

The marginal openings of cross-section shoulder width (mean of Sites X, Y, and Z) of the direct-lift technique using SM 90 porcelain (71.3 $\pm$17.0 micrometers) were significantly larger than either the platinum foil technique (26.6 $\pm$12.3 micrometers) or the direct-lift technique using high-fusing shoulder porcelain (37.8 $\pm$20.0 micrometers) (Tables 16 and 23). The platinum foil technique and the direct-lift technique using high-fusing shoulder porcelain were not statistically different from one another at this site.

H. Cross-Section Area of Rounding

The cross-section area of rounding of the direct-lift technique using high-fusing shoulder porcelain (55.7 $\pm$81.2 mm^2), the platinum foil technique (22.1 $\pm$30.8 mm^2), and the direct-lift technique using SM 90 porcelain (48.9 $\pm$26.8 mm^2) were not statistically different (Table 17). While the mean values may appear different, the large standard deviations did not make these differences statistically significant.

I. Cross-Section Area of Positive or Negative Rounding

Lastly, the data were regrouped into categories representing the nature of the porcelain rounding -- positive or negative (Table 9). This regrouping necessitated smaller and unequal sample groups.

1. Positive Rounding

The direct-lift technique using high-fusing shoulder porcelain (N=6, 18.7 $\pm$11.8 mm^2) produced a sharper positive porcelain margin than the direct-lift technique using SM 90 porcelain (N=6, 49.0 $\pm$30.5 mm^2) (Table 18). However, a comparison with the platinum foil technique was not possible because the platinum foil technique had only one specimen with positive rounding.

2. Negative Rounding

The cross-section area of negative rounding of the direct-lift technique using high-fusing shoulder porcelain (N=4, 111.3 $\pm$112.7 mm^2), the platinum foil technique (N=9, 24.6 $\pm$31.7 mm^2), and the direct-lift technique using SM 90 porcelain (N=4, 48.9 $\pm$24.7 mm^2) were not statistically different (Table 19).

TABLE 1. MEANS AND STANDARD DEVIATIONS OF FACIAL MARGIN

GROUP	N	MEAN (MICROMETERS)	STANDARD DEVIATION
Direct-Lift Shoulder Porcelain	10	8.16	1.98
Platinum Foil	10	13.69	4.56
Direct-Lift SM 90 Porcelain	10	11.25	4.61

TABLE 2. MEANS AND STANDARD DEVIATIONS OF CROSS-SECTION SITE X

GROUP	N	MEAN (MICROMETERS)	STANDARD DEVIATION
Direct-Lift Shoulder Porcelain	10	14.33	12.22
Platinum Foil	10	20.25	9.53
Direct-Lift SM 90 Porcelain	10	10.57	6.39

TABLE 3. MEANS AND STANDARD DEVIATIONS OF CROSS-SECTION SITE Y

GROUP	N	MEAN (MICROMETERS)	STANDARD DEVIATION
Direct-Lift Shoulder Porcelain	10	33.46	16.15
Platinum Foil	10	17.74	7.15
Direct-Lift SM 90 Porcelain	10	134.43	50.34

TABLE 4. MEANS AND STANDARD DEVIATIONS OF CROSS-SECTION SITE Z

GROUP	N	MEAN (MICROMETERS)	STANDARD DEVIATION
Direct-Lift Shoulder Porcelain	10	65.59	56.11
Platinum Foil	10	41.90	33.52
Direct-Lift SM 90 Porcelain	10	68.78	29.56

TABLE 5. MEANS AND STANDARD DEVIATIONS OF CROSS-SECTION H VALUE

GROUP	N	MEAN (MICROMETERS)	STANDARD DEVIATION
Direct-Lift Shoulder Porcelain	10	81.43	46.62
Platinum Foil	10	49.92	29.39
Direct-Lift SM 90 Porcelain	10	145.60	59.73

TABLE 6. MEANS AND STANDARD DEVIATIONS OF CROSS-SECTION L VALUE

GROUP	N	MEAN (MICROMETERS)	STANDARD DEVIATION
Direct-Lift Shoulder Porcelain	10	6.53	1.95
Platinum Foil	10	9.33	3.28
Direct-Lift SM 90 Porcelain	10	10.34	6.52

TABLE 7. MEANS AND STANDARD DEVIATIONS OF CROSS-SECTION SHOULDER WIDTH (SITES X, Y, AND Z)

GROUP	N	MEAN (MICROMETERS)	STANDARD DEVIATION
Direct-Lift Shoulder Porcelain	10	37.79	19.98
Platinum Foil	10	26.63	12.27
Direct-Lift SM 90 Porcelain	10	71.26	16.97

TABLE 8. MEANS AND STANDARD DEVIATIONS OF CROSS-SECTION AREA OF ROUNDING

GROUP	N	MEAN (MILLIMETERS^2)	STANDARD DEVIATION
Direct-Lift Shoulder Porcelain	10	55.72	81.22
Platinum Foil	10	22.11	30.84
Direct-Lift SM 90 Porcelain	10	48.93	26.84

TABLE 9. MEANS AND STANDARD DEVIATIONS OF CROSS-SECTION AREA OF ROUNDING - POSITIVE OR NEGATIVE

GROUP		N	MEAN (MILLIMETERS^2)	STANDARD DEVIATION
Direct-Lift	(+)	6	18.65	11.75
Shoulder Porcelain	(-)	4	111.33	112.65
	(+)	1	-	-
Platinum Foil	(-)	9	24.56	31.65
Direct-Lift	(+)	6	48.96	30.53
SM 90 Porcelain	(-)	4	48.89	24.67

TABLE 10. ONE-WAY ANALYSIS OF VARIANCE COMPARING FACIAL MARGINS ($p \leq .05$)

SOURCE	df	SS	MS	F-VALUE	F-PROB.
Between Groups	2	153.2259	76.6129	5.0057	.0142
Within Groups	27	413.2419	15.3053		
Total	29	566.4678			

TABLE 11. ONE-WAY ANALYSIS OF VARIANCE COMPARING CROSS-SECTION SITE X ($p \leq .05$)

SOURCE	df	SS	MS	F-VALUE	F-PROB.
Between Groups	2	476.2880	238.1440	2.5422	.0974
Within Groups	27	2529.2670	93.6766		
Total	29	3005.5550			

TABLE 12. ONE-WAY ANALYSIS OF VARIANCE COMPARING CROSS-SECTION SITE Y ($p \leq .05$)

SOURCE	df	SS	MS	F-VALUE	F-PROB.
Between Groups	2	80195.3847	40097.6923	42.2687	.0001
Within Groups	27	25613.2090	948.6374		
Total	29	105808.5937			

TABLE 13. ONE-WAY ANALYSIS OF VARIANCE COMPARING CROSS-SECTION SITE Z ($p \leq .05$)

SOURCE	df	SS	MS	F-VALUE	F-PROB.
Between Groups	2	4313.0887	2156.5443	1.2575	.3005
Within Groups	27	46305.2650	1715.0098		
Total	29	50618.3537			

TABLE 14. ONE-WAY ANALYSIS OF VARIANCE COMPARING CROSS-SECTION H VALUE ($p \leq .05$)

SOURCE	df	SS	MS	F-VALUE	F-PROB.
Between Groups	2	47551.1047	23775.5523	10.7991	.0004
Within Groups	27	59443.6370	2201.6162		
Total	29	106994.7417			

TABLE 15. ONE-WAY ANALYSIS OF VARIANCE COMPARING CROSS-SECTION SITE L VALUE ($p \leq .05$)

SOURCE	df	SS	MS	F-VALUE	F-PROB.
Between Groups	2	77.9207	38.9603	2.0504	.1482
Within Groups	27	513.0260	19.0010		
Total	29	590.9467			

TABLE 16. ONE-WAY ANALYSIS OF VARIANCE COMPARING CROSS-SECTION SHOULDER WIDTH (SITES X, Y, AND Z) ($p \leq .05$)

SOURCE	df	SS	MS	F-VALUE	F-PROB.
Between Groups	2	10788.2490	5394.1245	19.3236	.0001
Within Groups	27	7536.9868	279.1477		
Total	29	18325.2358			

TABLE 17. ONE-WAY ANALYSIS OF VARIANCE COMPARING CROSS-SECTION AREA OF ROUNDING ($p \leq .05$)

SOURCE	df	SS	MS	F-VALUE	F-PROB.
Between Groups	2	6318.8432	3159.4216	1.1463	.3328
Within Groups	27	74414.1743	2756.0305		
Total	29	80733.0175			

TABLE 18. ONE-WAY ANALYSIS OF VARIANCE COMPARING CROSS-SECTION AREA OF POSITIVE ROUNDING ($p \leq .05$)

SOURCE	df	SS	MS	F-VALUE	F-PROB.
Between Groups	1	2755.7852	2755.7852	5.1518	.0466
Within Groups	10	5349.1921	534.9192		
Total	11	8104.9773			

TABLE 19. ONE-WAY ANALYSIS OF VARIANCE COMPARING CROSS-SECTION AREA OF NEGATIVE ROUNDING ($p \leq .05$)

SOURCE	df	SS	MS	F-VALUE	F-PROB.
Between Groups	2	20863.8767	10431.9384	3.0484	.0796
Within Groups	14	47909.2733	3422.0909		
Total	16	68773.1500			

TABLE 20. TUKEY'S B-PROCEDURE MULTIPLE COMPARISON TEST OF FACIAL MARGINS

GROUP	N	MEAN (MICROMETERS)	STANDARD DEVIATION
Platinum Foil	10	12.69	4.56
Direct-Lift Shoulder Porcelain	10	8.16	1.98
Direct-Lift SM 90 Porcelain	10	11.25	4.61

Groups connected by a vertical line are not statistically different at $p \leq .05$

TABLE 21. TUKEY'S B-PROCEDURE MULTIPLE COMPARISON TEST OF CROSS-SECTION SITE Y

GROUP	N	MEAN (MICROMETERS)	STANDARD DEVIATION
Direct-Lift SM 90 Porcelain	10	134.43	50.34
Direct-Lift Shoulder Porcelain	10	33.46	16.15
Platinum Foil	10	17.74	7.15

Groups connected by a vertical line are not statistically different at $p \leq .05$

TABLE 22. TUKEY'S B-PROCEDURE MULTIPLE COMPARISON TEST OF CROSS-SECTION H VALUE

GROUP	N	MEAN (MICROMETERS)	STANDARD DEVIATION
Direct-Lift SM 90 Porcelain	10	145.60	59.73
Direct-Lift Shoulder Porcelain	10	81.43	46.62
Platinum Foil	10	49.92	29.39

Groups connected by a vertical line are not statistically different at $p \leq .05$

TABLE 23. TUKEY'S B-PROCEDURE MULTIPLE COMPARISON TEST OF CROSS-SECTION SHOULDER WIDTH (SITES X, Y, AND Z)

GROUP	N	MEAN (MICROMETERS)	STANDARD DEVIATION
Direct-Lift SM 90 Porcelain	10	71.26	16.97
Direct-Lift Shoulder Porcelain	10	37.79	19.98
Platinum Foil	10	26.63	12.27

Groups connected by a vertical line are not statistically different at $p \leq .05$

V. DISCUSSION

This study was intended to evaluate the accuracy of the direct-lift technique of fabricating porcelain labial margin metal ceramic restorations. Two types of shoulder porcelain were used for the direct-lift technique and their fit compared to porcelain labial margin metal ceramic restorations fabricated by the platinum foil technique using conventional body porcelain. Furthermore, computer technology was used to more accurately measure porcelain margin sharpness, or the amount of rounding that occurred at the margin when porcelain was fired.

A. Facial Marginal Opening

Statistical analysis revealed that the facial marginal openings of the platinum foil technique group (13.7 micrometers) were significantly larger than either of the direct-lift technique groups (shoulder porcelain - 8.2 micrometers and SM 90 porcelain - 11.3 micrometers) (Plates 12 and 13). A possible explanation for this outcome might be due to the fact that the platinum foil technique requires a second blocked-out stone working die on which to fabricate the restoration. This requires impressing the master die and pouring a second stone die. Furthermore, the porcelain is condensed against a piece of platinum foil which is adapted to the second working die. Even though the platinum foil is annealed and repeatedly burnished, its initial thickness is 0.001 inch (25 micrometers). In contrast, with the direct-lift technique the porcelain is condensed directly on the master die shoulder.

The facial marginal opening results of this study are similar to those obtained by Vryonis (1979), who reported marginal openings of 6 to 10

Plate 12. Facial View: Best Porcelain Labial Margins (x40)

A. Direct-Lift Technique Using High-Fusing Shoulder Porcelain (upper plate)

B. Platinum Foil Technique (middle plate)

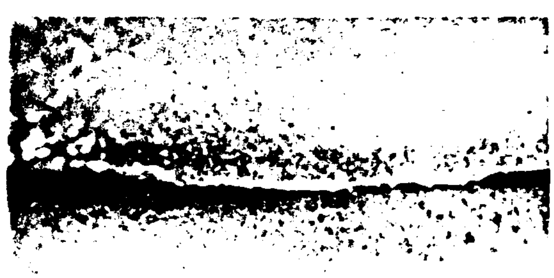
C. Direct-Lift Technique Using SM 90 Shoulder Porcelain (lower plate)

Plate 13. Facial View: Worst Porcelain Labial Margins (x40)

A. Direct-Lift Technique Using High-Fusing Shoulder Porcelain (upper plate)

B. Platinum Foil Technique (middle plate)

C. Direct-Lift Technique Using SM 90 Shoulder Porcelain (lower plate)



micrometers using the direct-lift technique and opaque porcelain. However, these findings differ markedly from the results of Cooney et al. (1985), who reported that the platinum foil resulted in a significantly better fit (32 to 38 micrometers) than a direct-lift technique (70 micrometers). A possible explanation for this difference may be that Cooney et al. used conventional body porcelain for their direct-lift technique, and not the more dimensionally stable high-fusing shoulder porcelains that were used in this investigation.

Furthermore the results of this study also compare favorably with the conclusion of Donovan and Prince (1985) that marginal gaps of only 6 to 34 micrometers can be consistently achieved using all-porcelain labial margins. Overall, all three fabrication techniques produced specimen facial marginal openings well below the practical range for clinical acceptability (50 to 75 micrometers) as reported by Hung et al. (1990).

B. Cross-Section Marginal Opening

The direct-lift technique using SM 90 porcelain (Vident) had a significantly greater marginal opening at three measurements sites than either the platinum foil technique or the direct-lift technique using high-fusing shoulder porcelain (Vident). The mean marginal opening at the midpoint Site Y was 134.4 micrometers for the SM 90 porcelain compared to 17.7 micrometers for the platinum foil technique and 33.5 micrometers for the direct-lift technique using high-fusing shoulder porcelain. The use of a midpoint (Y) was similar to the method of West et al. (1985). They reported a mean marginal opening ranging from 18.5 to 29.5 micrometers with the direct-lift technique using conventional body porcelain. In this study, a much larger marginal opening was noted at the midpoint with the direct-lift technique using SM 90 porcelain (134.4 micrometers).

A possible explanation for this difference in shoulder adaptation may be found in the properties of the SM 90 porcelain compounds. The SM 90 porcelain compounds contain a special binder which provides thermoplastic properties. When heated, these compounds become viscous, yet they harden as they return to room temperature. The binder helps the porcelain adapt easily to the die shoulder initially. But the high viscosity and low flow of the SM 90 require correcting the marginal opening that results from the sintering process by condensing the warm material (either 10 compound or 20 compound) into the gap from the facial, with the restoration completely seated on the die. Although an electric waxing instrument was used to maintain continuous heat, the material flowed axially less than half the width of the shoulder. Subsequent correction firings did adequately seal the most external site (Site X: 10.6 micrometers). However, a stepped configuration was seen on cross-section, with a large marginal opening at the midpoint (Site Y: 134.4 micrometers). This area was located far enough axially that the correction compound did not flow to it. Thus, it represents the marginal opening of one initial application of SM 90 porcelain and the shrinkage effect of multiple porcelain firings. This also explains the statistically significant difference in the highest (H) value (145.6 micrometers), which was located close to Site Y in all the SM 90 specimens. In addition, the mean marginal opening of the entire shoulder width was significantly greater for the SM 90 porcelain (71.3 micrometers) than for either the platinum foil technique (26.6 micrometers) or the direct-lift technique using shoulder porcelain (37.8 micrometers). Furthermore, the SM 90 porcelain had the widest range of marginal opening (10.3 micrometers [L] to 145.6 micrometers [H] along the shoulder of the three techniques studied. Thus, although the SM 90 porcelain sealed the margin

externally, statistical analysis showed it to be poorly adapted to the die shoulder internally. An uneven, poorly adapted shoulder may not resist the compressive forces of occlusion as well as an even, well-adapted shoulder of porcelain. However, this would have to be evaluated by further study.

In contrast to the uneven configuration of the SM 90 porcelain in cross-section, both the platinum foil technique and the direct-lift technique using shoulder porcelain produced a more uniform adaptation of the porcelain to the die shoulder. The porcelain margin with the platinum foil technique was uniform and well condensed in every specimen. Of the three techniques studied, it had the smallest range of marginal opening (9.3 micrometers [L] to 49.9 micrometers [H]) along the shoulder. While generally uniform in its adaptation, occasional small voids were observed along the shoulder with the direct-lift technique using high-fusing shoulder porcelain. These voids contributed to a marginal opening range of 6.5 micrometers [L] to 81.4 micrometers [H]. However, these voids were thought to be a result of operator technique and not the material itself, because the voids occurred at random locations and were not present in all specimens in this group.

Further evaluation of the cross-sectioned platinum foil specimens revealed that 8 of the 10 were undercontoured horizontally in relation to the stone die shoulder. Finishing of the porcelain margin in the platinum foil technique was completed on the blocked out stone working die. Thus, the operator was unable to visualize the emergence profile of the unprepared tooth because the root area of the die was blocked out and the platinum foil remained in place. Although Prince and Donovan (1983) reported that this lack of direct visualization of the margin during contouring was a disadvantage of the platinum foil technique, they gave no specific consequence of the effect.

This was only a qualitative observation. No attempt was made to measure the amount of undercontouring within the designs of this study. Although clinically an undercontoured margin does not accumulate as much plaque and is far less damaging to tissue than an overcontoured margin, it is nevertheless not an ideal situation (Holmes et al., 1989). A crown margin emergence profile that is continuous with the root surface is considered most desirable (Sorensen, 1990).

C. Rounding of the Porcelain Margin

Previous authors (Hunt et al., 1978; Cooney et al., 1985; West et al., 1985; Belles, 1987) have observed that porcelain labial margins fabricated with the direct-lift technique have a tendency to round during firing. Because no matrix is used to support the porcelain margin during sintering, the ceramic is free to shrink to the area of greatest bulk, and any sharply condensed porcelain margin rounds during firing. In contrast, with the platinum foil technique the foil matrix remains in contact with the condensed porcelain throughout the firing cycle. Thus, a sharply condensed porcelain margin is more apt to be preserved (Cooney et al., 1985; West et al., 1985).

The rounding of a porcelain labial margin has clinical relevance. Deviation from a sharp marginal configuraton can leave an unwanted gap at the tooth-restoration interface. This discrepancy can promote the accumulation of food debris, bacteria, and plaque and lead to the irritation of adjacent gingival tissues (Eissmann et al., 1971). Although the significance of this porcelain rounding has been acknowledged by authors (Hunt et al., 1978; West et al., 1985), none have reported measuring the degree of this rounding with their experimental designs.

Although there is no mention in the dental literature of a method to measure the rounding of porcelain labial margins, there are references to techniques for measuring the rounding of cast metal and cast ceramic margins. Brockhurst et al. (1983) reported the deficiency between the edge of a casting and the theoretical sharp edge as a straight line distance measurement. Bessing (1986) used a similar methodology in evaluating the marginal sharpness of various metal restorations, but he reported the rounding in terms of the diameter of a circle extrapolated from the observed rounding. Doyle et al. (1990) reported on the rounding of castable ceramics by measuring the marginal opening in cross-section at two locations -- the outer aspect of the margin and the inner aspect where rounding began. The distance between the two locations was the horizontal length of the rounding that occurred. Blackman et al. (1991) used computer images of marginal geometry derived from plotted horizontal and vertical reference points to calculate the marginal defect area of cemented titanium castings. In this study, a method was found to measure the rounding of the porcelain labial margin in cross-section using a computer software program (MacDraft).

The benefit of using computer technology for this mesurement is that it provides a quick, reliable, and thorough measurement of the exact configuration of the margin. The measurement is made from a standardized enlarged photograph of the specimen in cross-section. The MacDraft program is able to trace every irregularity of the rounded porcelain surface and calculate in total area the amount of rounding that occurs from the theoretical sharp edge. Since the area reported is calculated from an enlarged photograph, it is a larger value than actually exists. But if all specimens in each group are measured in the same manner, the area values will yield a meaningful relative comparison among groups.

Under microscopic examination, dental materials used to fabricate restoration margins (metal alloys, ceramics, resins) rarely exhibit the smooth uniform edge that is seen with the naked eye. The value of this computerized measuring method is that now a more accurate assessment of uneven surfaces can be obtained. This should yield measurements that more closely reflect the specimen configuration than previously reported point to point measurements.

Manufacturers' working instructions (Vident) for the materials used for the direct-lift technique state that both Vita VMK 68 shoulder porcelain (Vident) and SM 90 thermoplastic shoulder porcelain (Vident) are thermally stable compounds and will not round during firing. These claims have not been scientifically substantiated in the dental literature to date.

The results of this study showed that the mean area of labial margin rounding of the platinum foil technique group (22 mm^2) was smaller than the mean areas of either the direct-lift technique using shoulder porcelain group (55.7 mm^2) or the direct-lift technique using SM 90 porcelain group (48.9 mm^2). This would seem to indicate that the direct-lift technique did not produce a porcelain margin as sharp as the platinum foil technique. However, statistical analysis revealed no significant difference in the mean areas at a $p \leq .05$ level of significance. Therefore, it appears that high-fusing shoulder porcelains and the direct-lift technique can produce a porcelain labial margin as sharp as that produced with the platinum foil method. The results of this investigation quantitatively confirm the conclusions of Wanserski et al. (1986) and Arnold and Aquilino (1988), who observed that the "newer" shoulder porcelains appeared to have sharper margins than the body porcelains, but neither study included any measurement of marginal rounding.

During the measuring, it was noted that the porcelain margins of some of the specimens in the direct-lift technique followed the rounding of the stone

die external shoulder margin and actually went below the horizontal plane of the porcelain shoulder. These specimens were judged to have positive rounding of the margin (Figure 6). Obviously, the porcelain shoulder material was accurate and stable enough to follow the rounding of a stone die. This is a significant clinical finding. The rounded external margin of the stone die apparently failed to reproduce the sharp external margin of the tooth preparation. Clinically when this restoration is inserted in the patient's mouth, the overextended porcelain "tag" can either prevent the restoration from completely seating or fracture off during try-in, leaving a rough, unglazed area of porcelain, which can become a nidus for bacteria and plaque accumulation. If the fracture is large enough to compromise marginal integrity, the restoration would have to be remade.

The fact that the porcelain labial margins of the specimens rounded both above and below the horizontal plane of the porcelain shoulder (Figure 6) was an unanticipated finding. Therefore, a subsequent statistical analysis was performed after regrouping the data into categories representing the porcelain margin behavior: 1) positive rounding - porcelain rounding below the horizontal plane of the porcelain shoulder (Plate 14), 2) negative rounding - porcelain rounding above the horizontal plane of the porcelain shoulder (Plate 15). These new specimen groups, being subgroups of the original experimental design groups, were naturally small and unequal. Statistical analysis of the positive rounding specimens revealed that the direct-lift technique with shoulder porcelain produced a sharper porcelain margin (18.7 mm^2) than the direct-lift technique with SM 90 porcelain (49.0 mm^2). These results have a limited significance because they could not be compared to a platinum foil technique that had only one specimen with positive rounding. Statistical

Plate 14. Cross-Sectional View: Positive Rounding (x40)

A. Direct-Lift Technique Using High-Fusing Shoulder Porcelain (upper plate)

B. Platinum Foil Technique (middle plate)

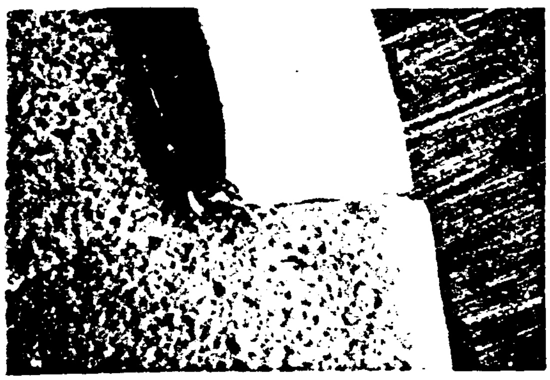
C. Direct-Lift Technique Using SM 90 Shoulder Porcelain (lower plate)

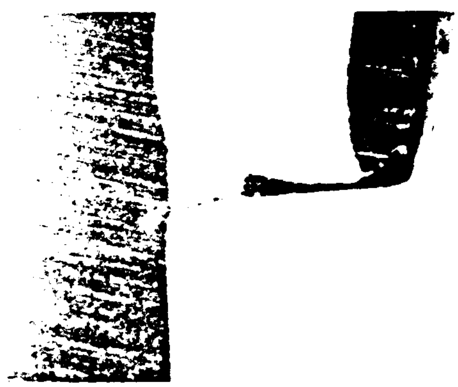
Plate 15. Cross-Sectional View: Negative Rounding (x40)

A. Direct-Lift Technique Using High-Fusing Shoulder Porcelain (upper plate)

B. Platinum Foil Technique (middle plate)

C. Direct-Lift Technique Using SM 90 Shoulder Porcelain (lower plate)





analysis of the negative rounding specimens revealed no significant difference among the three techniques - all produced a sharp porcelain labial margin.

The results of this study have shown that current porcelain materials have the potential to accurately produce a metal ceramic restoration with a sharp, externally sealed porcelain labial margin. Given these findings, perhaps the limiting factor in the clinical success of the porcelain labial margin metal ceramic restoration is the accuracy of the die material to reproduce the clinical tooth preparation rather than the actual margin porcelains. Although this investigation used only one stone die material (Silky-Rock), similar external margin rounding may be anticipated with other stone die materials. However, this would have to be verified by further study.

D. Future Research

This experimental design examined marginal adaptation and margin sharpness in fabricating the porcelain labial margin metal ceramic restoration. Future research in this area should include: (1) Evaluation of the accuracy of die materials used in fabricating porcelain labial margin metal ceramic restorations, (2) effect of a large internal marginal opening when the external margin is sealed, (3) compressive and tensile strengths of the porcelain margin fabricated with the various techniques and materials, (4) esthetic results of the newer shoulder porcelains, and (5) clinically related study examining marginal adaptation of the porcelain labial margin metal ceramic crown after cementation.

VI. SUMMARY

This investigation was designed to examine the porcelain margin characteristics of the porcelain labial margin metal ceramic restoration fabricated by three different techniques: 1) platinum foil technique using conventional body porcelain; 2) direct-lift technique using high-fusing shoulder porcelain; and 3) direct-lift technique using SM 90 shoulder porcelain. Marginal adaptation was evaluated from both a mid-facial and a cross-sectional view with the crowns seated on their respective master dies. In addition, a method was developed to use computer technology to accurately measure the porcelain margin rounding that occurs at the external labial margin when porcelain is fired.

The following results and conclusions can be drawn from this investigation:

1. The direct-lift technique produced specimens with significantly smaller facial marginal openings than the platinum foil technique ($p \leq .05$).
2. The direct-lift technique using SM 90 shoulder porcelain produced specimens with a significantly greater cross-sectional marginal opening at three different measurement sites (shoulder midpoint Site Y, highest point [H], and entire shoulder width) than either the platinum foil method using conventional body porcelain or the direct-lift technique using high-fusing shoulder porcelain ($p \leq .05$).
3. The SM 90 shoulder porcelain was not adapted uniformly to the stone die shoulder in cross-section.

4. In 8 of 10 specimens fabricated by the platinum foil technique, the porcelain labial margin was undercontoured horizontally in relation to the stone die shoulder.
5. The direct-lift technique, using either high-fusing shoulder porcelain or SM 90 shoulder porcelain, produced a porcelain labial margin as sharp externally as that produced with the platinum foil technique ($p>.05$).
6. The high-fusing shoulder porcelain and the SM 90 shoulder porcelain were accurate and stable enough to follow a rounding of the external shoulder margin of the stone die. This positive rounding or overextended porcelain "tag" could possibly prevent complete seating of the restoration clinically.
7. The limiting factor in the clinical success of the porcelain labial margin metal ceramic restoration may be the accuracy of the die material to reproduce the clinical tooth preparation rather than the margin porcelain or technique.
8. The results of this investigation suggest using the direct-lift technique and high-fusing shoulder porcelain to fabricate the porcelain labial margin metal ceramic restoration. However, care must be taken when trying in the restoration to identify and remove any overextended porcelain "tags".

APPENDIX

Raw Data for Test Specimens

TABLE 1A. FACIAL MARGINAL OPENINGS IN MICROMETERS

SPECIMEN		POSITIONS 1	2	3
Direct-Lift Shoulder Porcelain	1	7.9,6.9,6.6	9.6,6.1,6.1	3.6,2.5,4.8
	2	6.6,4.6,6.1	11.2,7.6,4.6	11.4,6.3,6.1
	3	13.5,7.4,13.2	13.5,18.5,16.8	5.6,10.2,5.8
	4	10.7,14.0,12.9	12.4,8.4,12.2	6.6,10.7,7.1
	5	10.2,12.7,11.7	7.4,6.6,6.1	6.6,8.1,6.9
	6	7.6,6.6,5.6	4.3,6.3,5.1	10.4,11.2,5.6
	7	10.7,7.1,8.4	9.9,12.9,9.6	11.2,8.4,10.4
	8	6.6,4.1,9.6	4.3,4.6,6.1	5.1,2.3,3.3
	9	3.0,7.9,7.9	14.2,8.1,6.3	10.4,6.1,8.9
	10	11.7,9.9,9.6	6.9,4.3,6.9	9.4,6.1,5.6
Platinum Foil	11	21.3,18.5,19.0	29.2,29.4,31.5	17.0,11.9,13.2
	12	9.6,5.6,7.9	10.9,7.1,6.3	15.0,8.9,9.4
	13	18.8,13.7,14.7	15.5,9.1,12.4	19.5,15.0,14.5
	14	15.5,17.3,13.5	10.7,6.1,7.1	9.9,6.6,7.6
	15	14.2,12.9,13.2	19.0,14.5,14.5	17.8,15.2,15.2
	16	13.7,9.9,15.5	23.1,21.6,20.1	31.0,24.4,21.3
	17	17.8,14.7,13.7	6.6,7.4,2.8	12.4,9.6,6.1
	18	8.6,8.1,5.6	8.4,7.4,7.9	12.7,7.6,8.4
	19	25.4,20.8,22.3	15.0,13.7,12.7	17.3,12.7,9.6
	20	14.2,11.9,10.2	10.4,8.4,8.1	16.2,12.7,9.1
Direct-Lift SM 90 Porcelain	21	9.4,7.9,5.6	10.2,6.6,6.1	8.4,5.6,6.3
	22	8.9,8.9,8.4	9.9,8.4,9.9	5.1,4.6,6.6
	23	13.2,13.2,9.1	18.5,16.5,17.0	13.7,10.9,8.1
	24	10.9,8.6,8.4	10.4,8.6,8.9	9.1,9.9,11.2
	25	9.4,7.4,7.1	8.6,4.6,6.3	8.1,5.6,7.4
	26	13.5,10.7,9.4	16.0,13.5,12.2	10.2,12.2,9.1
	27	9.6,10.9,9.6	8.9,8.9,7.6	10.7,7.9,10.4
	28	12.2,9.1,10.7	10.7,8.9,9.4	12.7,12.4,11.9
	29	19.8,20.1,19.0	22.8,25.4,22.6	25.9,26.6,24.4
	30	9.6,10.7,10.4	10.7,11.2,10.9	14.5,15.0,15.7

TABLE 2A. CROSS-SECTION MARGINAL OPENINGS IN MICROMETERS

SPECIMEN		SITES X	SITES Y	SITES Z
	1	11.9,9.9,10.9	17.8,14.0,14.7	50.3,49.5,48.5
	2	7.1,6.3,4.1	5.8,7.4,3.0	43.4,44.2,42.4
Direct-	3	10.7,10.7,10.7	37.1,38.1,35.8	83.5,84.0,82.7
Lift	4	46.4,45.4,44.7	28.4,21.6,25.6	21.8,23.9,20.1
Shoulder	5	23.9,23.9,19.5	33.0,33.2,33.8	23.4,21.8,19.8
Porcelain	6	6.9,3.0,5.8	52.5,50.5,49.7	103.0,100.0,100.5
	7	19.3,19.3,15.5	25.1,20.8,21.3	88.1,85.3,86.8
	8	7.9,7.4,6.1	42.4,41.1,40.1	29.2,30.7,27.2
	9	6.1,7.9,5.8	52.5,51.3,50.3	199.7,201.3,199.5
	10	11.7,11.7,9.9	53.6,52.5,51.5	19.0,18.5,19.0
	11	27.9,28.7,25.9	16.0,16.2,14.2	51.3,54.3,54.3
	12	10.9,11.9,11.4	19.0,19.0,18.8	17.3,16.8,15.7
Platinum	13	25.1,28.2,24.6	8.4,6.6,8.6	15.7,10.9,10.7
Foil	14	23.1,20.8,22.1	26.9,25.6,24.1	124.6,123.6,121.3
	15	37.6,37.6,36.5	28.9,29.7,29.7	23.4,27.2,24.1
	16	5.6,5.1,5.3	14.0,12.7,15.0	62.9,60.2,61.2
	17	15.2,15.2,15.5	12.7,11.4,10.9	52.3,54.6,55.8
	18	13.5,12.4,11.7	26.6,27.9,25.6	32.2,31.0,29.7
	19	26.6,27.4,27.4	15.0,11.9,15.2	29.4,28.4,21.8
	20	18.5,18.0,18.5	15.5,11.7,13,7	17.3,13.7,15.7
	21	9.6,8.1,7.4	150.5,151.5,149.5	67.3,65.0,62.2
	22	6.3,6.9,3.0	114.7,115.5,115.2	48.7,45.7,47.0
Direct-	23	23.1,20.8,23.6	60.2,65.5,62.4	26.9,25.6,29.2
Lift	24	10.7,7.6,7.9	168.3,166.8,166.0	55.6,54.3,53.3
SM 90	25	5.6,4.1,5.1	178.7,178.7,177.9	105.6,104.8,105.1
Porcelain	26	6.1,6.6,6.6	226.1,224.9,224.1	48.7,51.8.49.2
	27	6.3,5.6,5.8	60.4,58.9,59.4	129,9,129.4,130.2
	28	20.8,20.3,19.5	123.4,121.6,123.1	66.5,65.7,65.0
	29	14.2,14.2,14.7	136.5,138.1,136.5	73.1,69.5,68.5
	30	9.9,8.6,8.9	127.2,125.9,125.4	74.4,72.1,73.6

TABLE 3A. CROSS-SECTION MARGINAL OPENINGS
IN MICROMETERS*

SPECIMEN		HIGHEST (H) VALUE	LOWEST (L) VALUE
	1	72.8,68.8,67.8	6.3,5.8,6.1
	2	66.0,62.2,60.2	Y
Direct-	3	71.3,68.5,72.3	4.1,4.3,3.6
Lift	4	35.3,34.8,32.5	8.9,5.6,5.1
Shoulder	5	37.6,36.0,34.8	9.6,7.1,7.1
Porcelain	6	Z	6.1,4.6,5.3
	7	80.5,78.2,81.0	6.9,6.1,4.8
	8	71.8,71.3,69.8	X
	9	Z	4.8,6.9,5.1
	10	90.1,87.1,86.8	X
	11	62.9,59.4,58.1	10.9,8.6,11.4
	12	52.8,51.0,54.1	13.5,9.4,10.4
Platinum	13	23.6,26.6,22.3	8.1,7.9,5.6
Foil	14	Z	7.4,4.6,4.1
	15	37.6,33.0,34.0	15.2,15.0,13.7
	16	Z	X
	17	Z	6.9,5.6,6.1
	18	32.7,33.0,31.2	10.7,11.2,10.7
	19	32.0,30.5,29.4	13.7,15.0,10.4
	20	25.6,26.6,25.4	10.4,8.6,8.9
	21	Y	5.6,6.6,5.8
	22	163.5,159.9,158.9	X
Direct-	23	88.6,83.2,82.0	X
Lift	24	Y	X
SM 90	25	198.0,195.2,198.7	X
Porcelain	26	Y	X
	27	Z	X
	28	139.1,139.8,137.3	X
	29	185.0,184.5,179.9	X
	30	155.8,152.3,154.1	X

*Letters X, Y, or Z indicate value was the same location as previously measured site X, Y, or Z (Table 2A).

TABLE 4A. CROSS-SECTION AREA OF ROUNDING IN MILLIMETERS^2

SPECIMEN		AREA (+) ROUNDING	AREA (-) ROUNDING
	1	23.65	
	2	18.80	
Direct-	3	33.65	
Lift	4		268.95
Shoulder	5	25.80	
Porcelain	6		115.70
	7	2.15	
	8		36.70
	9	7.85	
	10		23.95
	11		1.85
	12		7.70
Platinum	13		46.15
Foil	14		53.80
	15		7.30
	16		13.65
	17		0.15
	18		90.10
	19		0.35
	20	0	
	21		34.90
	22		34.40
Direct-	23	96.15	
Lift	24	43.90	
SM 90	25	23.35	
Porcelain	26	10.20	
	27	59.25	
	28		85.65
	29		40.60
	30	60.90	

LITERATURE CITED

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